Minister’s foreword

On behalf of the Northern Territory Government, I welcome you to Alice Springs, and to the fourteenth Annual Geoscience Exploration Seminar.

While the new Territory Government acknowledges that these are challenging times for the junior exploration sector, we are committed to supporting and growing exploration in the Territory.

A strong and successful exploration industry is the key to growing our mining and energy sector, which is the Territory’s largest industry and an integral element of the Territory’s three-hub economy. For this reason we are implementing and supporting programs such as the pre-competitive geoscience initiative that are designed to stimulate exploration and lead to the next generation of mineral and petroleum discoveries in the Territory.

AGES plays an important role in demonstrating and promoting the Territory’s exploration potential. The event highlights the excellent work of the Northern Territory Geological Survey within my Department, as well as providing examples from industry of recent exploration success from across the Territory. The Government, through NTGS, is providing start-of-the-art new geoscience to highlight prospectivity and lower exploration risk, along with the provision of collaborative funding to support greenfields exploration. The Government is also committed to streamlining regulatory processes and assisting junior explorers in attracting international investment.

I trust that you will find the AGES conference both interesting and enjoyable, and that it will assist in your future exploration success in the Territory. As Minister for Mines and Energy, I strongly believe in the opportunities that the Territory offers explorers, and I look forward to continuing to work with the industry to ensure that the Territory is the destination of choice for mineral and petroleum exploration in Australia.

Hon. Willem Westra van Holthe, MLA
Site plan
Mining Services Expo, Alice Springs Convention Centre
19–20 March 2013

Booth and Exhibitor
01 & 02  Department of Mines and Energy
03 Bowgan Minerals Limited
04 The Alice Springs Watershed
05 Alice Bush Haulage & Mining Services
06 Thrifty
07 AutoSparky Parts
08 Energy Power Systems Australia P/L
09 CSA Global
10 Minerals Council of Australia - NT Division
11 Intertek
12 HELLA Australia
13 Chartair Pty Ltd
14 Alice Springs Helicopters
15 St John Ambulance NT
16 Arafura Resources Ltd
17 Ausurv Pty Ltd
18 Ausfuel Gull
19 Australian Mining and Exploration Title Services
20 ALSGroup
21 Bureau Veritas
22 Chubb Fire and Security
23 Territory Instruments
24 Indervon Pty Ltd
25 Territory Hirex
26 Brian Blakeman Surveys
27 Arnhem Exploration Services
28 NT Indigenous Business Network
29 ABM Resources
30 Navman Wireless
31 Emmerson Resources
32 Fluid Power NT Pty Ltd
33 Mithril Resources Ltd
34 Michels Warren Munday
35 TNG Limited
36 Core Exploration Limited
37 Urban & Rural Contracting/Atlas Plant Hire
38 Central Car Rentals
39 & 40 Central Communications / TJM
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<tr>
<td>8:00–8:30</td>
<td>Registration</td>
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<tr>
<td>8:50–9:20</td>
<td>Ian Scrimgeour, NTGS - Northern Territory exploration and mining overview 2012</td>
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<td>9:20–9:35</td>
<td>Fiona Park, DME - Helping NT explorers attract international investment</td>
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<td>9:35–10:00</td>
<td>Dot Close, NTGS - Highlights from recent NTGS geoscience programs</td>
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| 10:00–10:40 | Morning tea |}

### Session 1

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<tr>
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<tr>
<td>10:40–11:00</td>
<td>Tracey Rogers, NTGS</td>
<td>Geoscience information systems and services: what's new and what's coming</td>
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<td>11:00–11:20</td>
<td>Pascal Hill, ABM Resources NL</td>
<td>ABM Resources: Beyond Twin Bonanza - redefining the final frontier</td>
</tr>
<tr>
<td>11:20–11:40</td>
<td>Jo Whelan, NTGS</td>
<td>The Cu-Au potential of the Arunta Region: Links between magmatism, tectonism, regional-scale alteration and mineralisation</td>
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<tr>
<td>11:40–12:00</td>
<td>Patrick Lyons, Mithril Resources Ltd</td>
<td>Discovery of the Illogwa IOCG Belt: Mithril opens new exploration space in the east Arunta</td>
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<td>12:00–13:20</td>
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### Session 2

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<tr>
<td>13:40–14:00</td>
<td>Ana Liza, Emmerson Resources Ltd</td>
<td>Evolution of the Gecko Corridor, Tennant Creek Goldfield</td>
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<tr>
<td>14:00–14:10</td>
<td>Belinda Smith, NTGS</td>
<td>Spectral reflectance characteristics of type example rocks from the Tennant Creek mineral field</td>
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<td>14:10–14:25</td>
<td>Drew Wagner, Minerals Council of Australia, NT</td>
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<tbody>
<tr>
<td>15:10–15:30</td>
<td>Chris Edgoose, NTGS</td>
<td>Overview of the geology and mineral and petroleum resources of the McArthur Basin, NT</td>
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<tr>
<td>15:30–15:50</td>
<td>Ray Johnson, Armour Energy Ltd</td>
<td>Emerging hydrocarbon resources from exploration results in the Palaeoproterozoic intervals of the McArthur Basin, Northern Territory</td>
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<td>15:50–16:10</td>
<td>Andrew Stacey, Geoscience Australia</td>
<td>Unconventional prospectivity: Unconventional hydrocarbon resources in Australian basins, with a case study from the Georgina Basin</td>
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<td>16:10–16:30</td>
<td>Paul Burton, TNG Ltd</td>
<td>Advancing Mount Peake to production and exploration update on the Mount Hardy Copper Field</td>
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<td>19:00–late</td>
<td>Dinner speaker: Simon Bennison, CEO AMEC</td>
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**DAY 3** **Wednesday 20 March**

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<td>Roger Clifton</td>
<td>NTGS</td>
<td>Magnetic depths to extensive bodies</td>
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<td>Paul Dunbar</td>
<td>Energy Metals Ltd</td>
<td>Geophysical targeting of potentially uraniferous stratigraphy under cover, northern Ngalia Basin</td>
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<td>9:40–10:00</td>
<td>Tim Munson</td>
<td>NTGS</td>
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<tr>
<td>10:40–11:00</td>
<td>Susanne Schmid</td>
<td>CSIRO</td>
<td>COBRA - Amadeus Basin Project; an introduction and first results</td>
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<tr>
<td>11:00–11:20</td>
<td>Clive Foss</td>
<td>CSIRO</td>
<td>More revealing – new images of the Amadeus Basin from closely spaced gravity measurements</td>
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<td>Andy Browne</td>
<td>Alligator Energy Ltd</td>
<td>Alligator Rivers uranium: facts and fiction</td>
</tr>
<tr>
<td>11:40–12:00</td>
<td>Tony Lofthouse</td>
<td>Thundelarra Exploration Ltd</td>
<td>Carbonate platforms: here today, skarn tomorrow? Developments in the understanding of the mineralisation potential at Thundelarra's Allamber Project</td>
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<tr>
<td><strong>Session 3</strong></td>
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<tr>
<td>13:00–13:10</td>
<td>Belinda Smith</td>
<td>NTGS</td>
<td>Rare earth reflectance spectroscopy – some NT examples and exploration implications</td>
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<tr>
<td>13:10–13:30</td>
<td>Kelvin Hussey</td>
<td>Arafura Resources Ltd</td>
<td>New insights on the geology of the Nolans Bore rare earths deposit</td>
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<td>13:30–13:50</td>
<td>Geoff Eupene</td>
<td>Crossland Uranium Mines Ltd</td>
<td>The Charley Creek alluvial rare earths deposits, central Australia</td>
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<td>13:50–14:10</td>
<td>Clive Foss</td>
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<td>Reliable drill targeting from magnetic field data – some NT examples</td>
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<td>Closing remarks</td>
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**End AGES 2013**
AGES 2013 major sponsor
Networking ice-breaker drinks sponsor

AGES 2013 sponsors
Networking sundowner drinks sponsor

Networking pre-dinner drinks sponsor

Dinner wine sponsor

Coffee sponsor
Northern Territory exploration and mining overview – 2012

Ian R Scrimgeour

Exploration statistics

Following an unprecedented boom in mineral exploration in the Northern Territory that peaked in 2011, mineral exploration expenditure began to decline during 2012. According to Australian Bureau of Statistics (ABS) figures, mineral exploration expenditure in the Northern Territory in 2011/12 was a record $210.4M, up 8% on the previous record of $195.3M in 2010/11. Total Australian mineral exploration was $3.95B, up 34% from $2.95B in 2010/11, although a disproportionate amount of this increase was related to large iron ore projects in Western Australia and coal projects in Queensland. As a result, the Northern Territory’s share of total Australian expenditure dropped significantly from 6.6% to 5.3% of total Australian expenditure. However, the Territory was the only Australian jurisdiction to have had steadily increasing exploration expenditure every financial year from 2003/04 to 2011/12 (Figure 1).

Much of Australia’s recent exploration expenditure is in brownfields areas (defined by the ABS as exploration that is delineating or proving up an existing deposit with Inferred Resource status or higher). In Australia, the proportion of greenfields to brownfields exploration dropped from 35% to 31% in 2011/12. In comparison, the proportion of greenfields exploration in the Territory is higher than the national average, although it decreased from a record high of 59% in 2009/10 to 35% in 2011/12. This remains higher than the levels of greenfields exploration in the Territory prior to 2006, when it comprised only 25–30% of total expenditure on exploration.

According to ABS figures, in 2011/12, the top commodities by expenditure in the Territory were gold ($77.6M, up 57% on 2010/11), iron ore ($30.9M, up 15%), uranium ($29.0M, down 31%) and copper ($13.7M, up 15%). Expenditure for lead, zinc, nickel, cobalt and diamonds was relatively low. Exploration expenditure for ‘other’ commodities, which includes rare earths, phosphate, manganese, vanadium and multi-commodity projects, was down 27% to $35.7M (Figure 2).

Onshore petroleum exploration expenditure is not included in these figures and is not separately reported for the Northern Territory by the ABS. However, exploration expenditure figures publicly reported by companies suggest that onshore petroleum expenditure in the Territory was in excess of $100M in 2012.

Expenditure on mineral exploration in the Northern Territory has been in decline during 2012 (Figure 1). In the September 2012 quarter, mineral exploration expenditure was $47.4M, down 34% from the record of $71.6M, set in the September quarter in 2011. For the first three-quarters of 2012, mineral exploration expenditure was $119.1M, down 27% on the $161.3M in the first three quarters of 2011. This decline can be particularly attributed to drops in expenditure for uranium, iron ore and ‘other commodities’ from 2011 to 2012. Difficulties for junior explorers in raising funds for exploration are particularly affecting greenfields exploration across Australia.

At the end of 2012, there were 1482 granted non-extractive mineral exploration licences (compared with 1377 at the end of 2011) and 1006 exploration applications. During 2012, 300 applications were received and 411 were granted.

Exploration and mining highlights

Figure 3 shows selected exploration highlights for 2012. In the following summary of exploration and mining results

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1. Northern Territory Geological Survey, PO Box 4550, Darwin, NT 0801, Australia.
2. Email: ian.scrimgeour@nt.gov.au.
for the Territory during 2012, all resources stated are JORC-compliant or NI43-101-compliant unless stated otherwise. Most material cited here has been sourced from company websites, news releases and Stock Exchange announcements by companies. As a result, details of exploration by some private and other non-listed companies that do not report publicly could not be included. The Northern Territory Department of Mines and Energy also maintains a database of Northern Territory exploration news that can be accessed from: [http://geoscience.nt.gov.au/explornews.html](http://geoscience.nt.gov.au/explornews.html).

Mineral production statistics for the Northern Territory for 2011/12, collected under the NT Mineral Titles Act, are given in Table 1.

**Gold**

**Pine Creek Orogen**

Crocodile Gold Australia Pty Ltd continued gold production from their operations in the Pine Creek region, with the focus being on their flagship Cosmo Deeps underground mine (Figure 4), where production stoping commenced in September. Mining also occurred at open cuts at West Howley and Rising Tide early in 2012, but planned mining did not proceed at Princess Louise and North Point. Production from Crocodile Gold’s Northern Territory operations totaled 40 731 oz Au for the 2012 calendar year, down from 68 579 oz in 2011. No change in total resources was announced in 2012, with resources at Crocodile Gold’s projects in the Pine Creek Orogen remaining at combined Measured and Indicated Resources of 51.8 Mt at 1.9 g/t Au, and Inferred Resources of 36.3 Mt at 1.8 g/t Au, for a total resource of 5.32 Moz Au. The Cosmo Deeps deposit has an Indicated Resource of 5.3 Mt at 4.6 g/t Au and an Inferred Resource of 5.65 Mt at 3.7 g/t Au, for a total resource of 1.45 Moz Au. Exploration during 2012 included drilling at Union Reefs, Maud Creek and Rising Tide. At the Union Reefs project, Crocodile Gold undertook drilling at the Prospect and Crosscourse deposits to vertical depths of up to 400 m and along an expanded strike length of 650 m in order to confirm the continuity of several mineralised zones. Drilling beneath the Prospect pit yielded best intersections of 2.52 m at 240.4 g/t Au, 7.33 m at 11.87 g/t Au, and 12.61 m at 6.31 g/t Au, whereas beneath the Crosscourse pit, the best drill intersections included 3.16 m at 10.0 g/t Au. In October 2012, Crocodile Gold announced that they planned to commence open cut production from the International mine at Pine Creek in the second quarter of 2013, although the company subsequently announced that it plans to reassess this proposal.

In May 2012, Crocodile Gold signed a binding agreement with Primary Minerals NL for the sale of the Mount Bundy project area in the Pine Creek Orogen that includes the Toms Gully and Rustlers Roost deposits, and has a resource base in excess of 1 Moz of gold. In November 2012, Primary Minerals were purchased by Hydrotech International Ltd, and the merged entity plan to publicly list under the name Primary Gold Ltd in January 2013. A primary focus of the company is to dewater the Toms Gully underground mine and bring it back into production.

The Spring Hill gold deposit, 25 km north of Pine Creek, is hosted in greywacke and siltstone of the Mount Bonnie Formation, with gold occurring mainly in quartz veins that are concentrated in fracture zones and the axial zones of anticlines. Drilling by Thor Mining PLC since 2011 has led to a resource upgrade at Spring Hill with an Indicated Resource of 4.0 Mt at 2.32 g/t Au for 300 000 oz Au at a 1 g/t cut-off. The resource is calculated to a maximum depth of 150 m and remains open at depth. Notable results from drilling in 2012 included intersections of 11.0 m at 5.1 g/t Au from 65 m (including 6.0 m at 10.2 g/t Au) and 46.7 m at 2.9 g/t Au from 301 m. A 922 m conceptual drillhole targeting Callie-style mineralisation in the Koolpin Formation at depth beneath Spring Hill failed to intersect the targeted stratigraphy.

Vista Gold Corporation (Vista) continued to progress their Mount Todd project, northwest of Katherine. Mineralisation at the Batman orebody at Mount Todd is contained in a stockwork of quartz veins and their margins, within metamorphosed interbedded siltstone, shale and minor tuff of the Burrell Creek Formation. Proven and Probable Mineral Reserves at Mount Todd are 149.9 Mt at 0.85 g/t Au, for 4.11 Moz Au. Following an August 2012 resource upgrade, Measured and Indicated Resources at
Mount Todd are 261.4 Mt at 0.83 g/t Au for 7.01 Moz Au, and Inferred Resources are 88.8 Mt at 0.73 g/t Au for 2.09 Moz Au. Vista undertook a major resource conversion drilling program in the Batman orebody at Mount Todd during 2012, with intersections including 163 m at 1.5 g/t Au from 487 m (including 11 m at 7.38 g/t Au), 148.5 m at 1.32 g/t Au and 206 m at 1.03 g/t Au. In October 2012, Vista announced that it intends to complete a preliminary feasibility study in the second quarter of 2013. The company expects the first quarter of 2013 that evaluates a revised two-phased program in the Batman orebody at Mount Todd during 2013.

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**Tanami–Arunta regions**

The Tanami gold province straddles the Northern Territory—Western Australia border. There is currently one working mine in the Tanami Region in the Northern Territory, at **Callie**, operated by Newmont Mining Corporation (Newmont). Mineralisation at Callie consists of high-grade Au-quartz veins in folded carbonate sillstone in the lower part of the Dead Bullock Formation. Callie was discovered in 1991 and open cut mining commenced in 1995. As of 31 December 2011, the Proven and Probable Reserves at Newmont’s Tanami operations were 16.7 Mt at 4.31 g/t Au for 2.52 Moz Au, an increase of 480 000 oz on the previous year, with additional Measured and Indicated Resources of 4.1 Mt at 3.09 g/t Au and Inferred Resources of 10.4 Mt at 4.76 g/t Au. In November 2012, Newmont announced that they were deferring a $450M expansion of their Tanami operations that involved development of a shaft to support underground expansion at the Callie and the newly discovered **Auron** ore bodies.

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**Figure 3.** Map of Northern Territory showing selected highlights of exploration in 2012.
Tanami Gold NL have continued to increase resources at their Central Tanami project, which includes the historic Tanami goldfield that produced 2 Moz of gold from 43 open cuts between 1987 and 2005. The project area comprises multiple gold deposits within economic trucking distance of a 1.25 Mtpa treatment plant and associated infrastructure. In January 2013, the total resource for the Central Tanami project stood at 25.50 Mt at 3.2 g/t Au, for 2.63 Moz Au. Exploration in 2012 was largely focused on upgrading and extending the Groundrush resource and exploring satellite deposits. The historic Groundrush open cut is approximately 1.5 km in length, 100 m deep, and produced more than 600 000 oz of gold between 2001 and 2004, at a recovered grade of 4.3 g/t Au. The deposit is hosted within a thick fractionated dolerite unit and a secondary discrete high-grade quartz vein. Drilling in 2012 suggests that the mineralised system remains strong at depth and down plunge to the south of the current Mineral Resource. Drilling highlights in the past year include 17.0 m at 109.0 g/t Au from 322 m, 6.0 m at 51.5 g/t Au from 72 m, 30.1 m at 9.0 g/t Au from 329 m and 5.1 m at 21.7 g/t Au from 238 m. Drilling of newly identified down-plunge extensions to the south of the resource intersected high-grade vein-hosted mineralisation, with intersections including 38 m at 45.9 g/t Au from 421 m and 7 m at 13.8 g/t Au. The resource at the Groundrush deposit nearly doubled during 2012 to 6.72 Mt at 4.8 g/t Au, for 1.04 Moz Au. The mineralised system remains open at depth and in multiple directions. At the Ripcord prospect, 2.5 km south of Groundrush, a maiden resource has been defined of 1.1 Mt at 2.5 g/t Au. The Ripcord deposit shares numerous similarities with Groundrush including the same host dolerite, alteration assemblages, geometry and magnetic signature. Tanami Gold also drilled at the Beaver deposit during 2012, demonstrating the potential for resource extensions beneath the existing open cut, with a best intersection of 5 m at 6.5 g/t Au from 100 m. Tanami Gold are targeting the completion of a Definitive Feasibility Study for the Central Tanami project in April 2013.

ABM Resources NL (ABM) continued to have drilling success in 2012 in the Tanami Region, with much of their exploration focusing on the Old Pirate deposit and newly discovered extensions and nearby deposits. Mineralisation at Old Pirate occurs at the surface and comprises multiple, high-grade, gold-bearing quartz veins up to several metres wide in a folded sandstone/shale succession. Trench sampling by ABM along surface veins at Old Pirate (mainly reported in 2011), yielded a combined average assay over 726 m of sampled veins of 24.01 g/t Au. On the basis of drilling undertaken in 2011, a maiden resource of 1.67 Mt at 10.5 g/t Au (no top-cut) was announced in April 2012. Drilling at Old Pirate in 2012 focused on extensional targets and infill areas, and included a number of newly discovered high-grade veins. The Western Limb Vein at Old Pirate yielded an intersection of 5 m at 52.27 g/t Au from 163 m, and drilling of down-plunge extensions of the existing Old Pirate South anticline and resource area intersected 8 m at 24.14 g/t Au from 132 m. At the newly discovered Golden Hind prospect, 800 m south of Old Pirate, trench sampling of surface veins yielded an average assay over 60 m of sampled veins of 103.23 g/t Au, and results from initial drilling included 42 m at 44.02 g/t Au from surface and 17 m at 29.43 g/t Au from 29 m. During 2012, ABM released the results of a scoping study on Old Pirate, which suggested that the presence of high-grade coarse free gold allowed for construction of a simple gravity processing plant, making the project a potentially low-cost mining operation. The Stage 1 pit is modeled to contain 832 000 t at 11.5 g/t Au for 308 000 oz Au. A revision to this scoping study is pending and will include a new resource estimation, pit and underground design and a staged approach to development. ABM have applied for approvals to undertake bulk sampling and pilot gravity plant testing at Old Pirate to underpin a feasibility study.

The Buccaneer deposit, 2 m northeast of Old Pirate, has been interpreted to be a porphyry gold system, hosted within a porphyritic syeno-monzonite, and is the only significant granite-hosted gold system identified to date in the Tanami. In April 2012, ABM announced updated Inferred and new Indicated Resources for the Buccaneer deposit totaling 127.9 Mt at 0.65 g/t Au for 2.67 Moz Au,
including a higher-grade component of 36.9 Mt at 1.1 g/t Au for 1.57 Moz. ABM have interpreted an early disseminated gold phase with a later, structurally controlled higher-grade phase at Buccaneer. Highlights of drilling announced in 2012 included 41 m at 3.54 g/t Au from 287 m (including 6 m at 19.84 g/t Au) from the southwestern margin of the deposit and 31 m at 3.68 g/t from 365 m on southeastern extensions. The Cypress and Caribbean Zones, 1 km north of Buccaneer, comprise mineralisation in fractured and veined porphyry along the western margin of the intrusion, and intersections announced in 2012 included 22 m at 3.95 g/t Au from 238 m at Caribbean, and 6 m at 20.37 g/t Au from 187 m at Cypress.

ABM also announced a maiden resource for the Hyperion project, which is located 18 km north-northeast of the Groundrush deposit. Gold mineralisation at Hyperion is principally hosted in structurally controlled quartz-carbonate veins associated with felsic dykes and dolerites within metasedimentary rocks, and ABM consider the project area to have several geological similarities to the Groundrush deposit. Drilling results announced from Hyperion in 2012 include 35 m at 5.43 g/t Au from 36 m, and 17 m at 4.36 g/t Au from 146 m. On the basis of drilling in 2011, ABM announced a resource in April 2012 of 2.98 Mt at 2.11 g/t Au for 202 200 oz Au.

No drilling results were reported by ABM in 2012 from their projects in the Arunta Region, such as Kroda and Lake Mackay, although the company undertook major regional EM surveys, co-funded under the Geophysics and Drilling Collaborations program.

In November 2012, Ord River Resources Ltd announced a substantial increase in the resource estimate for their Suplejack project, based on drilling at the Tregony prospect, with a resource of 2.44 Mt at 1.29 g/t Au for 101 300 oz Au, with a higher grade component of 0.65 Mt at 3.02 g/t Au.

**Copper, copper-gold and copper-gold-silver**

**Arunta Region**

Copper exploration continued to be strong in the Arunta Region, which in recent years has been a focus for geological investigations by NTGS. The region has been increasingly recognised for its greenfields potential for a range of copper mineralisation styles.

During 2012, Kentor Gold Ltd commenced a bankable feasibility study at the Jervois copper-silver-gold project, northeast of Alice Springs, in the Aileron Province. Mineralisation at Jervois occurs in a series of stratabound, subvertical sulphide-rich deposits along a 12 km strike length in the 1807 Ma Bonya Schist. The field was mined intermittently in the last century, including an open cut operation at the Green Parrot deposit in the early 1980s. In November 2012, the company announced an upgraded resource for the Jervois project of 13.5 Mt at 1.3% Cu and 25.8 g/t Ag, for 170 416 t Cu and 11.6 Moz Ag, with most of the resources being in an Indicated category. The company also included a maiden gold resource of 12.7 Mt at 0.17 g/t Au for 69 000 oz Au. At the Reward-Marshall deposit, the resource is 8.3 Mt at 1.35% Cu, 29.3 g/t Ag and 0.22 g/t Au, and at Bellbird, the resource is 4.4 Mt at 1.13% Cu, 7.3 g/t Ag and 0.08 g/t Au. The company undertook an extensive drilling campaign during 2012, both for metallurgical test work under the feasibility study, and to infill and extend the resource. At the Reward prospect, drilling to the north of the resource intersected high-grade mineralisation, including 9.05 m at 4.9% Cu, 66.2 g/t Ag and 1.22 g/t Au from 430 m vertical depth, whereas drilling within the existing resource intersected 60 m at 1.73% Cu, 3.81% Pb, 1.15% Zn, 113.3 g/t Ag and 0.21 g/t Au from 7 m (10 m estimated true width) and 12 m at 3.72% Cu, 40.7 g/t Ag and 0.68 g/t Au from 63 m. At Marshall, drilling results include 21.4 m at 3.0% Cu, 0.4% Pb, 0.4% Zn, 40.1 g/t Ag and 0.38 g/t Au from 95 m. Drilling to the west of the Marshall deposit intersected a new zone of shallow mineralisation, with 32 m at 1.1% Cu, 1.2% Pb, 1.4% Zn, 60.4 g/t Ag and 0.12 g/t Au, from surface. This zone may be a northern extension of the Green Parrot orebody, which occurs 500 m to the south. At Bellbird (Figure 5), drilling at the northern end of the deposit has resulted in the highest-grade gold intersection reported at Jervois, with 6 m at 1.2% Cu, 10.43 g/t Ag and 12.43 g/t Au from 64 m. Other results from Bellbird included 10 m at 4.64% Cu, 23.5 g/t Ag and

**Figure 5.** Drilling at Bellbird deposit, Jervois, June 2012.
0.1 g/t Au from 67 m. On the basis of interpretation of the ASTER dataset released by NTGS in May 2012, Kentor Gold have discovered a new prospect area, named Chubko, 3 km east-southeast of Bellbird, with anomalous copper and gold in outcrop. Kentor Gold moved to a feasibility study on the Jervois project in April 2012, after a scoping study based on annual processing rates of 1.5 Mtpa, 2 Mtpa and 2.5 Mtpa found that the project was robust and would produce strong financial returns, with open cut mining in the first three years followed by underground mining from years 3 to 7.

In October 2012, Rox Resources Ltd signed a farm-in agreement with Arafura Resources Ltd to explore the Bonya copper project in the Bonya Hills, near Jervois. Reconnaissance at the project has yielded high-grade rock-chips from a number of prospects across the Bonya Hills, including 30.7% Cu, 34.1 g/t Ag and 0.44 g/t Au from the Bonya Mine prospect and 7.72% Cu and 0.64 g/t Au from Green Goanna. Drilling of targets is expected in the first half of 2013.

Mithril Resources Ltd (Mithril) undertook a significant exploration program at their Illogwa IOCG project area in the Arunta Region south of the Harts Range, following the identification by NTGS (announced at AGES 2011) of widespread haematite and fluorite alteration in the area. Initial exploration by Mithril in 2011 identified a number of new, apparently structurally controlled, iron oxide copper-gold (IOCG) prospects associated with these alteration systems, along a 40 km-long structural trend. In 2012, a reconnaissance drilling program of 2300 m of aircore, RC and diamond drilling at the project was focused at the MiniMe, El Gordo, Goldmember, Nigel, Austin, and Bigglesworth prospects. At Austin, diamond drilling of IP anomalies, modelled to lie directly beneath outcropping haematite alteration ± copper mineralisation, intersected over 100 m of strongly altered (quartz–haematite–fluorite) and brecciated granite with disseminated and stringer sulfides including chalcocypirite. At El Gordo, RC drilling intersected 14 m at 0.34% Cu, 1.26 g/t Ag and 0.04 g/t Au from 18 m, including 2 m at 1.15% Cu, 5.3 g/t Ag and 0.23 g/t Au, and at Nigel, the best intersection was 10 m at 0.34% Cu from 10 m. Mithril have undertaken a VTEM survey, with follow-up IP surveys at priority anomalies, with a view to generating specific drill targets for 2013.

Mithril announced a maiden JORC resource at their Basil copper prospect, within their Huckitta project area in the Harts Range. Basil is a greenfields discovery made in 2009, and comprises a 10 km-long trend of copper-bearing gossanous outcrop and hydrothermal alteration, associated with a large-scale EM anomaly. The Inferred Resource, which covers the Peaks and Rotten Hill zones at Basil, stands at 26.5 Mt at 0.57% Cu, 504 ppm Co, 11.3% S and 25.4% Fe (at 0.3% Cu cut-off) or 90 Mt at 0.28% Cu and 309 ppm Co (at 0.1% Cu cut-off). Mineralisation is associated with massive (20–50%) and stringer sulfides, comprising pyrrhotite, pyrite and chalcopyrite, within mafic amphibolite of the Irindina Province, close to a crustal-scale shear zone that forms the contact with the Aileron Province. No further drilling was reported at Basil during 2012.

Mithril also undertook reconnaissance exploration at their Yambah project area in the Strangways Range northeast of Alice Springs, with rock-chip samples including 11.85% Cu, 36.8 g/t Au and 34.4 g/t Ag at the Turners prospect. During 2012, Transol Corporation Ltd entered into a joint venture agreement with Sturt Resources Ltd on its Southern Cross Bore project, in the Strangways Range 75 km northeast of Alice Springs, which includes the Johnnies Reward Au-Cu prospect. Drilling at Johnnies Reward in May–June 2012 confirmed gold-copper mineralisation extending for 200 m down plunge from surface, with intersections including 24 m at 4.19 g/t Au and 0.33% Cu from 79 m and 34 m at 3.83 g/t Au and 0.44% Cu from 63 m. The gold-copper mineralisation occurs in a pyrite-chalcopyrite-bearing magnetite-pyroxene skarn and is also noted within the footwall quartz-biotite-garnet-magnetite gneiss. The mineralised skarn has now been intersected over a strike length of 200 m north of the Johnnies Reward

### Table 1. Mineral production figures for 2011/12 (excluding extractive minerals).

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<thead>
<tr>
<th>Commodity</th>
<th>Unit of Quantity</th>
<th>2011–12 Quantity</th>
<th>$ Amount for Quantity Sold</th>
<th>2011–12 Total Minerals</th>
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<tr>
<td><strong>Metallic Minerals</strong></td>
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**Metallic Minerals Value**

$2,595.2

**Energy Minerals**

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<th>Commodity</th>
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<th>2011–12 Quantity</th>
<th>$ Amount for Quantity Sold</th>
<th>2011–12 Total Minerals Value</th>
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<td>Uranium Oxide</td>
<td>Tonnes</td>
<td>3,284</td>
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</table>

**Total Minerals Value**

$2,826.3

**Explanatory Notes**
1. Fiscal year is 1 July to 30 June.
2. Data is from production returns lodged by operators under statutory obligations.
3. Amount for Quantity Sold is in Australian Dollars and presumed to be the gross amount paid to the operator.
4. Data has been rounded and autosum applied.
5. Data is correct as at 07 November 2012 and may be subject to revision due to late lodgements and/or receipt of superior data.
6. On 1 July 2009, a new production structure was implemented based on full annual processing rate and actual commodity produced off-site. The previous structure had been based on actual commodity available from mining before processing if sold or worked on-site or off-site. The structure change should be considered when comparing previous years’ data.
7. Alumina and alumina hydrate are derived from bauxite. Processing input and output data is deemed operator commercial-in-confidence.
8. Quantity produced represents total bauxite production. Quantity sold and $ excludes input for alumina production. Processing input and output data is deemed operator commercial-in-confidence.
9. 100% gold. This does not include the gold constituting the metallic content of gold concentrate.
10. Estimated metallic content of gold concentrate is 81% gold and 19% silver.
gossan. A second phase of drilling in late 2012 intersected further broad zones of mineralisation including 22 m at 1.23 g/t Au and 1.21% Cu from 117 m.

TNG Ltd undertook the first modern exploration program at the Mount Hardy copper field, in the western Arunta Region north of Yuendemu. A HeliTEM survey over the field in mid-2012 identified a number of EM anomalies, which were followed up by rock-chip sampling that identified numerous samples with high-grade copper, and locally high-grade gold, silver, lead and/or zinc. The company drilled 7 RC holes for 1712 m, with the first hole intersecting 12 m at 0.65% Cu, 0.39% Pb and 0.87% Zn from 117 m, including 1 m at 2.35% Cu, 1.16% Pb and 3.08% Zn. Assays on other holes are pending. Historic BMR core that was drilled in 1968 at the Mount Hardy Mine was resampled at the NTGS Core Facility in Alice Springs, and included intersections of 10.7 m at 4.1% Cu from 7 m and 7 m at 1.64% Cu from 38 m. TNG are planning IP, gravity and downhole EM surveys at Mount Hardy in early 2013.

In April 2012, Kidman Resources Ltd acquired a tenement package over the Home of Bullion prospect in the northern Arunta Region near Barrow Creek. A 31 hole, 3990 m RC drilling program that was undertaken in 2012 intersected high-grade polymetallic mineralisation. Intersections from the Main Lode included 5 m at 6.5% Cu, 53 g/t Ag, 0.63% Pb, 2.75% Zn and 0.61 g/t Au from 174 m, 6 m at 4.3% Cu, 103.6 g/t Ag, 2.03% Pb, 6.96% Zn and 0.48 g/t Au from 105 m and 6 m at 3.2% Cu, 94 g/t Ag, 4.28% Pb, 15.5% Zn and 0.29 g/t Au from 95 m. Drilling of the Southern Lens at the prospect resulted in a best intersection of 7 m at 1.78% Cu and 29.3 g/t Au from 18 m in the oxide zone. Kidman considers the deposit to be a unique style of zone polymetallic mineralisation, consisting of high-grade copper, gold, and silver, locally containing zones of massive magnetite. Fixed loop and downhole electromagnetic surveys have generated further targets for drilling in 2013. Kidman Resources has also undertaken geophysical surveys to generate targets for copper-nickel sulfide exploration at Prospect D, 30 km north of Home of Bullion.

**Tennant Region**

Tennant Creek-style IOCG orebodies are believed to have resulted from mineralised hydrothermal fluids passing along shear zones and reacting with Proterozoic iron-rich sedimentary rocks of the Warramunga Formation, resulting in what are now steeply plunging, zoned, high-grade Au-Cu-Bi sulfide orebodies. Exploration for this style of orebody is focused on the historic Tennant Creek mineral field, and on the Rover field, where Tennant Creek-style mineralisation occurs beneath 150–300 m of overlying Wiso Basin sedimentary rocks.

In the Tennant Creek mineral field, Emmerson Resources Ltd undertook further drilling at their 2011 copper-gold discoveries, Monitor and Goanna, in the Gecko mine corridor. Monitor and Goanna were discovered on the basis of HeliTEM surveys that identified sulfide-rich mineralisation that had not been detected by previous geophysical techniques in the field. The mineralisation typically comprises chalcopyrite-quartz-chlorite veins bounded by sub-vertical shear zones, in dilational zones within the Gecko structural corridor. It represents a different mineralisation style to the typical magnetite ironstone-hosted deposits at Tennant Creek. At Goanna, mineralisation is largely controlled by at least five sub-parallel shear zones that trend northwest–southeast. Within these shear zones are discrete high-grade ore shoots that occur as quartz-chlorite-sulfide tension vein arrays and also as haematite-chlorite-ironstones. Drilling intersections announced at Goanna during 2012 included 26 m at 4.75% Cu from 338 m (including 8 m at 9.32% Cu) and 3 m at 11.9% Cu. Drilling of the Southern Shear Zone at Goanna resulted in an intersection of 24.1 m at 4.12% Cu and 0.19 g/t Au from 358 m, associated with intense talc-chlorite-haematite alteration and chalcopyrite in cross-cutting quartz vein arrays, and an intersection of 9 m at 3.18% Cu and 984 ppb Bi from 427 m within a thick zone of haematite–chlorite alteration replaced by chalcopyrite-bismuth veins. Drilling within the Northern Shear Zone at Goanna intersected a new ore zone containing 13 m at 1.77% Cu and 0.48 g/t Au from 393 m. Drilling of an eastern extension of the mineralisation at Goanna East (81 m at 0.45% Cu from 420 m including 3 m at 2.14% Cu) and at Horner 3 potentially doubled the strike length of the mineralisation to at least 600 m. In late 2012, Emmerson commenced a drilling program at the Orlando deposit, 4 km west-southwest of Gecko, which has a 2011 Resource of 0.98 Mt at 1.4% Cu and 2.0 g/t Au. Under the terms of the $28M farm-in and joint venture between Emmerson Resources and Ivanhoe Australia Ltd, the Gecko and Orlando areas of interest have been carved out of the JV, with Emmerson funding and retaining 100% ownership. Numerous greenfields HeliTEM targets await testing.

The Rover field, which is 70 km southwest of Tennant Creek, has been the focus of considerable recent success in exploration for Tennant Creek-style orebodies. The most advanced exploration project in the Rover field is the Rover 1 deposit, which straddles tenements owned by Metals X Ltd (formerly Westgold Resources Ltd), who have the majority of the defined orebody, and Adelaide Resources Ltd. The deposit has an Indicated and Inferred Resource of 6.8 Mt at 1.73 g/t Au, 1.21% Cu, 2.1 g/t Ag, 0.14% Bi and 0.1% Co for 1.22 Moz AuEq (gold equivalent), with a high-grade gold zone of 1.32 Mt at 7.01 g/t Au and 0.81% Cu. In April 2012, Westgold submitted a Mine Management Plan for an exploration decline at Rover 1 to undertake infill and extensional drilling. During 2012, the company drilled two holes 350 m east of the Rover 1 resource targeting a deep IP anomaly and intersected alteration, but no significant mineralisation.

During 2012 Adelaide Resources undertook evaluation and 3D-modelling of the Rover 4 prospect, 2 km north of Rover 1, which is a copper-gold system of similar style to Rover 1. The study suggested that Rover 4 is likely to be too small to develop in its own right, but has the potential to play a role as a source of secondary feed for a mill processing ores from the Rover field. Adelaide Resources also announced the results of 2011 drilling at their Rover 12 prospect,
20 km west-northwest of Rover 1, which was designed to test a large untested area in the western part of the prospect. The holes intersected shear zone-hosted mineralisation that included 4 m at 5.57 g/t Au and 1.22% Cu and 2 m at 5.08% Cu and 0.35 g/t Au, and ironstone-hosted mineralisation that included 17 m at 0.76% Cu. The company suggested that the shear zone-hosted mineralisation is potentially analogous to the shear zone-hosted mineralisation discovered by Emmerson Resources in the Gecko mine corridor.

In the Tomkinson Province, drilling by OM Manganese Ltd at a copper prospect at Chugga North, near the Bootu Creek manganese mine, intersected 7 m at 1.12% Cu from 10 m.

Pine Creek Orogen and McArthur Basin
Thundelarra Exploration Ltd undertook further drilling in 2012 at their Allamber uranium-copper project, north of Pine Creek. Newly identified mineralisation at the Tarpon-South Brumby trend at Allamber occurs within granite of the Cullen Supersuite, and is hosted by southeasterly dipping and northeasterly-plunging laminated quartz-sulfide sheets containing pyrrhotite, pyrite and chalcopyrite, with intersections including 5 m at 1.24% Cu from 54 m, 2 m at 2.40% Cu from 14 m and 2 m at 1.56% Cu from 11 m. At Nipper, drilling intersected potentially skarn-related Au-Cu-Sn-W mineralisation in sulfidic calc-silicate altered dolostone, with 8 m at 0.52% Cu, 0.15% W and 0.2 g/t Au from 90 m.

Redbank Copper Ltd has a substantial land holding in the McArthur Basin near the Queensland border, including the Redbank project, where copper mineralisation is hosted in breccia pipes. Total Indicated and Inferred JORC resources for the Redbank project area are 6.24 Mt at 1.5% Cu for 95 900 t of Cu. In 2012, Redbank’s exploration program was suspended pending restructure and recapitalisation of the company, although an airborne magnetic survey was undertaken over the area of their Wollogorang joint venture with Gulf Mines Ltd.

In the Pine Creek Orogen, carbonaceous shale within the Whites Formation, close to the contact with the underlying Coomalie Dolostone, hosts several polymetallic prospects and orebodies. HNC (Australia) Resources Pty Ltd (HAR)’s Browns project in the Pine Creek Orogen has an oxide resource of 9.4 Mt at 0.82% Cu, 0.14% Co and 0.14% Ni, and a sulfide resource of 45.1 Mt at 0.35% Cu, 3.74% Pb, 0.73% Zn, 0.09% Co and 0.07% Ni. The project remains on long-term care and maintenance.

Lead-zinc-silver

The McArthur River mine, situated about 70 km southwest of Borroloola, in the McArthur Basin (Figure 6), is operated by McArthur River Mining Pty Ltd (MRM), a subsidiary of Xstrata PLC. It opened as an underground mine in 1995 and has since been converted to open cut. At 31 December 2011, the McArthur River mine had total Measured and Indicated Resources of 162.2 Mt at 10.7% Zn, 4.7% Pb and 48 g/t Ag; total Reserves of 49.6 Mt at 9.6% Zn, 4.2% Pb and 43 g/t Ag. In 2011/12, MRM produced 449 000 t of bulk zinc and zinc-lead concentrate. The very fine-grained, thinly bedded sulfide ore is hosted in the HYC Pyritic Shale Member of the Barney Creek Formation. In August 2012, the Xstrata board gave final approval for the S360M Phase 3 Development Project at McArthur River, which will lead a doubling of production capacity to approximately 5.5 Mtpa and an increase in bulk zinc/lead concentrate volume to 800 000 tpa. The expansion will extend the life of mine by eleven years to 2038. The Phase 3 Development is scheduled to be commissioned in 2013 and will reach full production in 2014.

A joint venture between Teck Australia Pty Ltd and Rox Resources Ltd continued exploration in the Myrtle-Reward project area, east and south of McArthur River. During 2012, a detailed review of past exploration data by Teck revealed evidence of high-grade zinc mineralisation intersected by Mount Isa Mines Ltd in 1976–1978, 10 km due west of McArthur River, at a prospect now known as Teena. This historic core was located by Teck and re-assayed, yielding results that were consistent with historic assays, including 11.3 m at 10.9% Zn+Pb and 14 g/t Ag from 909 m, and 8.6 m at 9.84% Zn+Pb and 23 g/t Ag from 790 m. Follow-up exploration at this significant new prospect is expected in 2013. The Myrtle prospect, 20 km south of McArthur River, contains near-surface zinc-lead mineralisation with a strike length of at least 700 m along the Main Zone of mineralisation, and this remains open in all directions. The Inferred Resource at Myrtle is 43.6 Mt at 4.09% Zn and 0.95% Pb, at a 3% Zn+Pb cutoff, with a higher-grade core of 15 Mt at 5.45% Zn and 1.0% Pb. During 2012, drilling was conducted by the joint venture that confirmed extensions of the mineralisation to the north and east in the ‘North Myrtle basin’, albeit at relatively low grades, with intersections including 7 m at 2.52% Zn+Pb from 290 m and 22 m at 1.26% Zn+Pb from 160 m.

Sandfire Resources Ltd undertook a diamond drilling program in the second half of 2012 at the Rosie Creek and Alice prospects in the McArthur Basin. Drilling focused on geological and geophysical targets adjacent to the Emu Fault to test for SEDEX-style lead-zinc potential, and geochemical results are pending.

Admiralty Resources Ltd undertook an exploration program at their Bulman project in Arnhem Land, which encompasses the historic Bulman zinc-lead field. Mineralisation is largely hosted in carbonate rocks of the Dook Creek Formation of the McArthur Basin. In 2012, Admiralty Resources undertook ground-based EM surveys over anomalies selected from an airborne EM survey undertaken in 2011. The company also undertook 1000 m of RC drilling, for which results are pending.

At the Jervois base metals project in the Arunta Region, Kentor Gold Ltd have a lead-zinc-silver resource of 1.0 Mt at 2.6% Pb, 2.2% Zn and 73 g/t Ag at the Green Parrot deposit, as part of a much larger copper-silver resource. Metallurgical drilling at the Reward prospect in 2012 also yielded high-grade base metals, including 97 m at 17.3% Pb, 3.3% Zn, 2.2% Cu and 423 g/t Ag from 51 m, within an interval of 60.0 m at 3.81% Pb, 1.15% Zn, 1.73% Cu and 113 g/t Ag from 7 m.

Crocodile Gold Corp announced drilling results from its Iron Blow massive sulfide deposit in the Pine Creek
Orogen, which indicated the presence of both a base metals and a precious metals system associated with massive sulfides, and a peripheral gold-enriched system that is associated with only very minor sulfides. Drilling results from Iron Blow that were announced in 2012 include 20.3 m at 13.92% Zn, 3.1% Pb, 5.89 g/t Au, 481.85 g/t Ag and 0.2% Cu. Iron Blow has a resource of 3.17 Mt at 3.28% Zn, 0.76% Pb, 2.08 g/t Au, 100.9 g/t Ag and 0.19% Cu. In December 2012, Crocodile Gold entered into a binding letter of intent with TSX-listed Pitchblack Resources Ltd, for Pitchblack to acquire a 90% interest in base metals assets in the Pine Creek Orogen, including Iron Blow, the Mount Bonnie Pb-Zn-Au-Ag massive sulfide deposit and the Mount Evelyn Zn-Pb-Ag skarn.

**Diamonds**

During 2012, North Australian Diamonds Ltd (which changed its name to Merlin Diamonds Ltd in December 2012) continued to undertake feasibility studies for a proposed diamond mining operation at their Merlin Project in the McArthur Basin. The Merlin Project comprises 14 kimberlite pipes, of which nine were subject to open cut mining between 1998 and 2003, producing 507,000 ct of diamonds. The combined Probable Ore Reserve for all diamond pipes at Merlin is 11.1 Mt at 0.26 carats per tonne (ct/t) for a total of 2.89 Mct, and the Indicated and Inferred Mineral Resource is 19.02 Mt at 0.24 ct/t for a total of 4.31 Mct. The company undertook a range of studies aimed at optimising material processing, diamond liberation and detection techniques, and generating plant configuration designs. A 3000 m drilling program in the Merlin area, targeting geophysical and geochemical anomalies, commenced in late 2012. Merlin Diamonds have announced that they plan to commence production at the Merlin mine in the first quarter of 2013.

Merlin Diamonds commenced exploration costeaming at the Lancelot prospect, 40 km south of Merlin, targeting coincident geophysical and geochemical anomalies. In late 2011, the company undertook bulk sampling on the Borrooloola alluvial diamond project, targeting a major alluvial concentration in a catchment known to host diamond deposits. The bulk sampling program extracted 5000 t of material from five locations, of which 3000 t has been processed at Merlin, yielding 22 stones with a total weight of 1.09 ct.

**Bauxite and alumina**

The Gove bauxite mine and alumina refinery continues to be a major contributor to the Territory economy, and is operated by Pacific Aluminium, which is a subsidiary of Rio Tinto. The resource at Gove includes a Proved Reserve of 111 Mt at 49.5% Al₂O₃ and a Probable Reserve of 64 Mt at 49% Al₂O₃. In 2011, Pacific Aluminium announced production of 7.25 Mt of bauxite from the mine, with refinery production of 2.55 Mt of alumina. In late 2012, Pacific Aluminium was investigating options for converting the Gove refinery to gas, contingent on the availability of gas supply and construction of a pipeline. Pacific Aluminium have stated that may suspend operation of the refinery if a gas supply cannot be secured. Exploration for bauxite has been fairly limited in the Territory, although Rio Tinto Exploration Pty Ltd has been exploring on the Cato Plateau in partnership with BHP Minerals Pty Ltd.

**Iron ore**

 Territory Resources Ltd, which is owned by Singapore-listed Noble Group, has operated an iron ore mine at Frances Creek since 2007. The iron mineralisation occurs in a fault breccia in the lower Wildman Siltstone and ranges in composition from haematite to goethite and limonite. There are over 50 named occurrences and prospects covering a distance of approximately 35 km. Resources and reserves at Frances Creek announced in 2010 included a total Probable Reserve of 5.8 Mt at 57.9% Fe and Indicated and Inferred Resources of 9.9 Mt at 58.1% Fe. In 2011/12, Territory Resources produced 2.23 Mt of iron ore from Frances Creek (Table 1).

Significant iron ore projects continued to move towards production in the Roper iron field in the McArthur Basin. Iron ore in the Roper field varies from massive to oolitic and pisolithic haematite, and occurs within interbedded medium- to very coarse-grained ferruginous sandstone and siltstone of the Mesoproterozoic Sherwin Ironstone Member. Western Desert Resources Ltd (WDR) made significant progress in 2012 towards development of an iron ore mine at their Roper Bar project. The total Mineral Resource Estimates at Roper Bar stand at 402 Mt at 40.0% Fe, 28.0% SiO₂, 2.5% Al₂O₃, 0.005% P and 9.7% LOI, including a global direct shipping ore (DSO) component of 32.1 Mt at 56.8% Fe. During 2012, WDR announced an upgraded Resource for Area E (East) at Roper Bar of 71.6 Mt at 41.5% Fe including a DSO component of 16.64 Mt at 54.2% Fe, 15.9% SiO₂, 1.2% Al₂O₃, 0.004% P and 4.0% LOI, as well as an increased Resource for Area E (South). At Area F the Mineral Resource has been upgraded to 30.1 Mt at 48.8% Fe, including a DSO component of 15.5 Mt at 59.5% Fe, 9.6% SiO₂, 2.2% Al₂O₃, 0.006% P and 2.1% LOI. Subsequent deeper drilling at Area F (east) included 20 m at 62.7% Fe from 96 m, 28 m at 64.2% Fe from 164 m and 23 m at 65.0% Fe from 183 m. This drilling also established continuity of mineralisation at depth between Area F (East) and Area E (South). WDR also announced results of drilling of 133 holes at Area B, 20 km southwest of Area F, which confirmed the presence of haematite mineralisation that is typically 5 m thick, averaging 45% Fe with metre assays up to 62.6% Fe. WDR has commenced construction of a haul road from the Roper Bar leases to a barging facility at Bing Bong on the Gulf of Carpentaria, and have a number of regulatory approvals in place for development of a mine. The company plans to commence DSO production from Roper Bar in 2013. Sherwin Iron Ltd (Sherwin) continued exploration at their Roper River project, located around 100 km west and northwest of the Roper Bar project. The Roper River project has Indicated and Inferred Resources of 488 Mt at 41.7%
Fe, including a higher-grade component at 33.8 Mt at 57.4% Fe, 12.8% SiO₂, 1.6% Al₂O₃, 0.05% P and 2.6% LOI. Much of the exploration in 2012 was focused on infilling higher-grade potential DSO resources at Sherwin Creek (Area C) and Hodgson Downs (Areas W and X) to the Indicated category, with 225 RC holes drilled for 4453 m. At Sherwin Creek, which has a Resource of 320 Mt at 40.1% Fe, 34.4% SiO₂, 1.82% Al₂O₃ and 0.006% P, drilling at Deposit C in 2012 defined a high-grade Resource of 18.4 Mt at 58.3% Fe, 12.36% SiO₂, 1.07% Al₂O₃, 0.03% P and 2.47% LOI, almost all of which is in the Indicated category. The Sherwin Creek resource is contained within two separate layers (Middle and Lower) that are shallow, continuous and open down dip. Hodgson Downs, 70 km southwest of Sherwin Creek, has Indicated and Inferred Resources of 152.5 Mt at 44.8% Fe, 29.9% SiO₂, 2.1% Al₂O₃ and 0.03% P, and a higher grade Inferred Resource of 15.5 Mt at 57.1% Fe, 12.6% SiO₂, 2.2% Al₂O₃ and 0.10% P. In June 2012, Sherwin completed a scoping study on the Roper River project, and announced a preferred development option to commence with DSO production from Deposit C at Sherwin Creek. Transport of the ore would be by road to a river barge loading facility on the Roper River, then by barge to ships approximately 40 km offshore. The company plans to commence with a 3 Mtpa DSO operation, increasing to 6 Mtpa. Processing of low-grade ore (Stage 2) would commence after 2 years, with full production capacity planned to be 10 Mtpa.

During 2012, Aard Metals Ltd were conducting feasibility studies on their Warrego tailings project, 36 km northwest of the township of Tennant Creek. The project area comprises five tailings dams from the historical mining of ironstone-hosted copper and gold. Aard Metals are evaluating the project with a view to the production of a magnetite concentrate, with copper and gold as potential by-products. The project has an Indicated Resource of iron (as magnetite) for the Warrego tailings of 7.72 Mt (dry) at 35.2% Fe, upgradable to a concentrate of 2.92 Mt at 67.1% Fe. This is accompanied by an Inferred copper and gold resource of 7.79 Mt (dry) at 0.21% Cu and 0.48 g/t Au.

Manganese

Oolitic and piscolitic ore in Mesozoic sedimentary rocks on Groote Eylandt in the Gulf of Carpentaria forms one of the world’s highest-grade manganese deposits of 170 Mt at 47.1% Mn. It was discovered in 1960 and has been continuously mined by the Groote Eylandt Mining Company (GEMCO) for decades. Production from Groote Eylandt in 2012 totaled a record 4.771 Mt of manganese ore, a 21% increase due to a substantial increase in plant availability. The $280M Phase 2 expansion of the GEMCO operation, increasing GEMCO’s beneficiated product capacity to 4.8 Mtpa is expected to be completed in 2013. Northern Manganese Ltd have granted tenements over marine waters offshore from Groote Eylandt, where the company has interpreted the manganese orebody to extend below the seafloor. In March 2012, the Northern Territory Government placed a three-year moratorium on seabed exploration and mining.

The other operating manganese mine in the Northern Territory occurs in Proterozoic rocks at Bootu Creek, 110 km north of Tennant Creek. OM Manganese Ltd began mining operations at Bootu Creek in November 2005. At 31 December 2011, the total Mineral Resources were 32.3 Mt at 22.3% Mn and Ore Reserves were 17.4 Mt at 20.7% Mn. During 2012, OM Manganese mined 1.43 Mt of ore at 23.03% Mn, resulting in full year manganese production of 737 766 t grading 36.55% Mn. The company undertook a drilling program in 2012, focused on the discovery of new manganese deposits, including the testing of gradient array IP targets, and to a lesser extent on the partial replacement of resources depleted by mining. Phase 1 of the program, involved 215 holes for 11 062 m of drilling, with results including 9 m at 28.7% Mn from 23 m at Shekuma North and 3 m at 35.5% Mn from 6 m at Helen Springs.

Bligh Resources Ltd commenced exploration at their Bootu Creek Two manganese project, 40 km south of Tennant Creek.
of Bootu Creek with a 785 line-km Variable Time-Domain Electromagnetic (VTEM) survey that identified 10 anomalies, with a follow-up drilling program planned for 2013. In September 2012, Bligh exercised an option to acquire 80% of an adjacent tenement from Universal Splendour Investments Pty Ltd.

There were few public announcements on manganese exploration in the Northern Territory during 2011, although a number of companies were exploring for manganese, including Universal Splendour Investments Pty Ltd (Amadeus, McArthur and Birrindudu basins) and Sinosteel Australia Pty Ltd (Tomkinson Province and McArthur Basin).

**Molybdenum–tungsten**

During 2012, Thor Mining PLC released resource updates and a definitive feasibility study for their Molyhil molybdenum-tungsten project, near the Plenty Highway, northeast of Alice Springs. Molyhil is a skarn-related scheelite-molybdenite-magnetite deposit within the Arunta Region. In January 2012, Thor announced an increased resource of 4.71 Mt at 0.28% WO₃, 0.22% MoS₂ and 18.1% Fe, most of which is in the Indicated category. The deposit has an open cut Probable Ore Reserve of 1.64 Mt at 0.42% WO₃ and 0.13% MoS₂. The definitive feasibility study indicated positive financial returns over a four-year mine life, with capital expenditure of $70M. Thor are continuing to investigate upside potential based on optimising the pit design and have also identified further regional exploration targets to increase the tungsten-molybdenum resource in the area.

**Nickel**

Mithril Resources Ltd (Mithril) has discovered Ni-Cu-PGE mineralisation at several locations in their Huckitta project area in the eastern Arunta Region, including the Baldrick prospect, where drilling in 2009 yielded a best result of 9 m at 0.48% Ni and 0.37% Cu. Under a $4M option and joint venture between Mithril and MMG Exploration Pty Ltd, relating to the nickel rights on Mithril’s wholly owned tenements in the Huckitta project area, MMG undertook on-ground exploration in the Huckitta area during 2012. This included a helicopter-supported regional stream sediment survey involving the collection of 270 stream sediment and heavy mineral concentrate (HMC) samples at an average catchment density of <5 km².

In the previously unexplored Warumpi Province in the southwestern Arunta Region, Metals X Limited announced rock chip samples of up to 1.64% Ni in weathered dunite that has been mapped over approximately 1 km of strike.

**Vanadium-titanium-iron**

TNG Ltd’s Mount Peake project is a gabbro-hosted vanadium-titanium-magnetite prospect in the northern Arunta Region, 60 km west-southwest of Barrow Creek, with a JORC Indicated and Inferred Resource estimate of 160Mt at 0.3% V₂O₅, 5.0% TiO₂ and 23.0% Fe. This resource is expected to be upgraded in early 2013, following significant metallurgical, infill and resource extension drilling undertaken in 2012. In July 2012, TNG released the results of a pre-feasibility study on the Mount Peake project, which indicated robust financial returns, based on an 20-year mine life, initially of 2.5 Mtpa, expanding to 5 Mtpa after 3 years, with life-of-mine revenues of $11.4 billion. The proposed average annual production is 15 300 tpa V₂O₅, 375 000 tpa TiO₂ concentrate and 1.13 Mtpa Fe₂O₃. TNG have a strategic partnership with Jiangsu East China Mineral Investment & Development Bureau (ECE), who invested $13.4M in TNG during 2012 to assist in the development of Mount Peake. TNG are expected to make a decision on commencing a Definitive Feasibility Study in early 2013.

Arafura Resources Ltd reported further assays from drilling carried out in 2008 at their Jervois vanadium project in the Arunta Region northeast of Alice Springs. This included 13 m at 0.9% V₂O₅, 9.8% TiO₂ and 38.0% Fe from surface and 35 m at 0.6% V₂O₅, 5.7% TiO₂ and 25.2% Fe from 52 m at the Coco prospect, and 34 m at 0.4% V₂O₅, 4.4% TiO₂ and 21.7% Fe from 62 m at the RD prospect. The company also reported elevated platinum group elements associated with vanadium magnetite mineralisation, including 47 m at 0.57 g/t Au+Pt+Pd from 26 m at the Casper prospect (including 4 m at 1.17 g/t Pd, 0.17 g/t Pt and 0.03 g/t Au).

**Graphite**

Thundelarra Exploration announced its first graphite intersections from its Allamber project area in the Pine Creek Orogen. The company considers that significant potential for graphite exists along the 18 km strike length of a carbonaceous shale unit of the Masson Formation between the Hattrick and Cliff South prospects. Drilling by Thundelarra along the margin of the Cullen Granite within the Masson Formation has intersected wide sections of graphitic schist, with results of 36 m at 7.23% TGC (total graphitic carbon) at Hattrick and 28 m at 8.74% TGC at Cliff South. The highest assay result was 10.1% TGC for an 8 m composite section from a drillhole at Cliff South.

TNG Ltd have commenced metallurgical test work on graphite mineralisation intersected during diamond drilling in their Mount Peake project area in the northern Arunta Region. Drilling of a major 500 m by 200 m electromagnetic anomaly by TNG in 2011 failed to intersect base metals mineralisation, but subsequent inspection revealed that it intersected approximately 40 m of graphite mineralisation. A 2006 drillhole, located 100 m to the south, has been re-investigated and intersected >80 m of graphite, suggesting that the EM anomaly represents conductive graphite. No assays on the graphite have been released to date.

**Mineral sands (zircon-ilmenite-rutile)**

MZI Resources Ltd (formerly Matilda Zircon Ltd) commenced production of zircon and titanium concentrate at their Lethbridge South mineral sands mine on Melville
Island in the Tiwi Islands (Figure 7) in early 2012. The mine life has been extended through delineation of extensions to the resource and mining is expected to be completed in January 2013. During 2012, MZI exported three shipments of zircon and titanium concentrates for a total of nearly 25,000 t of concentrate, with fourth and final shipment of 6,500 t of concentrate due for export in the first quarter of 2013. The focus for MZI on the Tiwi Islands will then move to Kilimiraka on southwestern Bathurst Island. The Kilimiraka deposit has an inferred resource of 56.2 Mt at 1.6% heavy minerals, for 893,700 t of heavy minerals, comprising 92,000 t zircon, 57,000 t rutile, 127,000 t leucoxene and 368,000 t ilmenite. Matilda reported that the Kilimiraka resource has the potential to underpin an 8 to 10-year mining operation, assuming mining rates of approximately 700 t per hour. MZI plans to complete further drilling and feasibility studies at Kilimiraka in 2013.

Australian Ilmenite Resources Pty Ltd’s Roper Heavy Mineral project is targeting ilmenite-bearing Derim Derim dolerite sills in the Roper Group and associated placer deposits. This project has a Measured Resource of over 300,000 t ilmenite with a further 4 Mt either Indicated or Inferred. The ilmenite is very low in deleterious minerals such as Cr₂O₃, U and Th, and is suitable for the production of both synthetic rutile and titanium sponge.

Rare earth elements

During 2012, Arafura Resources Ltd (Arafura) announced a major resource upgrade at their Nolans Bore rare earth elements-phosphate-uranium orebody, located in the Reynolds Range, 135 km northwest of Alice Springs. Measured, Indicated and Inferred Resources total 47 Mt at 2.6% rare earth oxides (REO), 11% P₂O₅ and 0.02% U₃O₈. The orebody contains 1.22 Mt REO, 5.4 Mt P₂O₅ and 8830 t U₃O₈. A maiden Probable Ore Reserve for Nolans Bore was announced in December 2012, and is estimated at 24 Mt at 2.8% REO, 12% P₂O₅, 0.02% U₃O₈. The new resource was based on a major resource drilling campaign in 2011, comprising 52,169 m of RC and diamond core drilling. Nolans Bore is a hydrothermal, stockwork vein-style REE deposit, hosted in metasedimentary and igneous rocks of the Aileron Province of the Arunta Region. Apatite mineralisation at Nolans Bore ranges from discrete, narrow fine-grained veins to wide intervals of massive coarse-grained breccia. The rocks comprise up to about 95% apatite and typically contain abundant mineral inclusions of REE-bearing minerals, such as monazite-group minerals, allanite, thorite and numerous other REE phosphates, silicates and carbonates. As part of the feasibility study for the Nolans project, Arafura have established a Base Case for the project, which is expected to produce 20,000 tpa of REO products, with phosphate, uranium and gypsum co-products over a mine life in excess of 20 years, with a net present value of $4.3 billion. The life of mine schedule is based on a maximum overall annual mining rate of 7 Mtpa for the first eight years of the operation, increasing to 15 Mtpa thereafter to produce an average of 1.5 Mt of plant feed each year.

During 2012, exploration by TUC Resources Ltd focused on their heavy rare earth elements (HREE) discovery at Stromberg, 200 km south of Darwin. In 2011, assaying of samples from earlier uranium drilling at Stromberg identified significant HREE mineralisation hosted within flat-lying, near-surface sandstone, with up to 7 m at 1.0% TREO (total rare earth oxides). Follow-up drilling in late 2011 demonstrated the existence of coherent zones of mineralisation over a strike length of over two kilometres, with a best intersections of 8 m at 0.72% TREO (total rare earth oxides). Step-out drilling in 2012 significantly increased mineralised envelopes, with intersections including 3 m at 0.82% TREO from 7 m (comprising 2.3% HREE) and 5 m at 0.43% TREO (comprising 81.9% HREE). From all drilling to date, an average of 85.8% of the TREO are heavy rare earth elements, with key elements including dysprosium (comprising 7.5% of total REE distribution), yttrium (64.9% of distribution), erbium (4.8%), and terbium (ca 1%). The mineralisation also contains appreciable scandium (59 ppm Sc average).
The deposit contains significant uranium, but the thorium content is extremely low. The HREEs are contained in xenotime, with a significant level of HREE associated with clay. TUC consider that the free physical state and fine nature of the xenotime make the material more amenable to leaching. First-pass metallurgical test-work using a multistage leach process was positive, with 85% TREO recovery, 88% uranium recovery and 93% scandium recovery. In late 2012, TUC undertook metallurgical diamond drilling at Stromberg, with assays pending.

TUC Resources also undertook drilling at the Scaramanga HREE prospect, 5 km NNE of Stromberg and encountered mineralisation that is geologically similar, although lower grade than the mineralisation at Stromberg. Drill intersections included 5 m at 0.1% TREO from 10 m (comprising 70.0% HREE including 7.3% Dy) and 2 m at 0.12% TREO (comprising 81.2% HREE including 7.0% Dy). In September 2012, TUC announced that Traditional Owners had lifted a Moratorium on exploration on ELA 27151, which contains large (8 x 1 km) radiometric anomalies that are similar to those at Stromberg and Scaramanga, but at a larger scale. Reconnaissance exploration of these prospects, named Skyfall and Largo, is scheduled to commence in 2013.

Crossland Uranium Mines Ltd (Crossland) has defined a maiden resource of alluvial rare earths at its Charley Creek project, 120 km west of Alice Springs. The resource is contained within unconsolidated alluvial outwash, sourced largely from the Teapot Granite Complex in the Warumpi Province to the south. The deposit includes an Indicated Resource of 387 Mt at 295 ppm TREO and an Inferred Resource of 418 Mt at 289 ppm TREO. The combined resource includes 235 150 t of contained TREO, and contains 57 965 t xenotime and 328 135 t monazite. The resource also contains 415 560 t zircon as a potential by-product. Given the high xenotime content, the proportion of heavy REE is high, with approximately 17% of TREO being heavy REO. The resource was defined within the Western Dam and Cattle Creek prospect areas, but Crossland estimates that these resources represent less than 5% of the total area of the potentially mineralised outwash within their tenements. A pilot plant program evaluating Wet and Dry plants (gravity separation methods, followed by magnetic and electromagnetic separation) has been completed, and produced a heavy minerals concentrate product averaging 41.25% TREO at a recovery of 77.6% TREO. The result suggests that a xenotime/monazite concentrate can be produced at Charley Creek using a conventional mineral sands flow sheet. Downstream hydrometallurgical test work has commenced on xenotime-monazite concentrates, with encouraging early results. Crossland have announced that they plan to proceed with a scoping study to investigate the viability of a 12 Mt per annum mining project and mineral processing plant.

The Tanami Region also has high potential for rare earths. In the Browns Range, in WA within 10 km of the NT border, Northern Minerals Ltd have defined a maiden JORC Resource of 1.44 Mt at 0.73% TREO (comprising 84% HREE) at the Wolverine deposit. A large tenement package on the adjacent side of the border within the Northern Territory was granted to Northern Minerals during 2012 and includes the Boulder Ridge occurrence, which has historic rock chip samples up to 21.7% TREO, and where xenotime mineralisation has been noted in historical reports, hosted in quartz veins within silicified and brecciated sandstone.

**Phosphate**

In 2012, significant additional phosphate resources were defined in the Northern Territory, particularly in the Georgina Basin, which is a world-class province for sedimentary phosphorite. Since the beginning of 2011, 785 Mt of ore has been added to the Territory’s phosphate resource base (at 10% P₂O₅ cut-off), effectively doubling the JORC-compliant resources in the Georgina Basin within the Northern Territory in a two year period.

Minemakers Ltd’s Wonarah phosphate deposit occurs in the Cambrian upper Gum Ridge Formation or basal Wonarah Formation within the Georgina Basin, close to the Barkly Highway. In October 2012, Minemakers announced an updated resource for Wonarah with combined Measured, Indicated and Inferred resources (at 10% P₂O₅ cut-off) of 842 Mt at 18% P₂O₅, comprising 707 Mt in the Main Zone and 135 Mt in the Aruwwurra deposit. Minemakers also commenced a revised Bankable Feasibility Study that is considering two technical options for Wonarah's development: (1) a traditional wet acid process with the production of high-analysis granular phosphate fertilisers, such as DAP and MAP, at Tennant Creek, including on-site beneficiation and a slurry pipeline to Tennant Creek; (2) Improved Hard Process (IHP) kiln technology, involving the production of high-value superphosphoric acid on site. An RC drilling program was undertaken in late 2012 targeting high-grade shallow phosphate north of the main zone, and to investigate the western target area for its prospectivity for future production.

Rum Jungle Resources Ltd continued resource definition and metallurgical studies at the Barrow Creek 1 deposit (Figure 8), which was discovered in 2010 and forms part of their Ammaroo project. This project, which is approximately 80 km from the Alice Springs–Darwin railway, has emerged as the most significant new phosphate discovery in the Georgina Basin in recent decades. During 2012, Rum Jungle undertook a major drilling program to convert much of the resource at Barrow Creek 1 to Measured or Indicated status. As part of the program, 1214 RC holes were completed for 35 757 m, and drill intersections included 11 m at 28.2% P₂O₅ from 26 m (including 8 m at 32.8% P₂O₅) and 13 m at 23.1% P₂O₅ from 9 m (including 4 m at 30.7% P₂O₅). Following the 2012 drilling program, a Measured Resource of 136 Mt at 15.7% P₂O₅ has been defined as part of a total Measured, Indicated and Inferred Resource of 238 Mt at 14.6% P₂O₅ (at a 10% P₂O₅ cut-off). The area of the total resource is 6.9 km east–west by 5.3 km north–south. The average thickness of the deposit is 6.1 m with an average depth to the top of mineralisation of 22 m. Rum Jungle Resources consider that the Measured Resources provides increased confidence.
for a substantial mine life producing beneficiated phosphate rock at up to 2 Mtpa. The updated resource provides a basis for conceptual mine planning, metallurgical test work and process flowsheet development that is occurring as part of a scoping study due for completion at the end of March 2013.

Nupower Resources Ltd (Nupower) announced a maiden resource at their Arganara deposit, which is an eastern continuation of the Barrow Creek-1 deposit. The Inferred Resource totals 310 Mt at 15% P₂O₅ (at a 10% P₂O₅ cut-off) or 120 Mt at 18% P₂O₅ (at a 15% cut-off). The area of the existing resource is 5.8 km east–west by 5.4 km north–south, with an average thickness of 7 m. The resource estimate is based on results from 387 RC holes for 14 480 m of drilling. Highlights of drill intersections from Phase 2 and 3 drilling programs announced in 2012 included 7 m at 24.2% P₂O₅ from 28 m (including 1 m at 30.1% P₂O₅) and 5 m at 29.3% P₂O₅ from 14 m (including 2 m at 33.9% P₂O₅). Following regional drilling through the broader Arganara project area, NuPower have reported that they have defined a 27 km-long corridor of phosphate mineralisation extending from Arganara to the Limestone Bore prospect. The company also undertook soil sampling at regional prospects, including Rockhole Bore (formerly Anomaly L).

Rum Jungle Resources undertook a drilling program at the Ammaroo-1 prospect in April 2012, and intersected thick intervals of phosphate including 19 m at 21.61% P₂O₅.

Phosphate Australia Ltd undertook no work in 2012 on their Highland Plains deposit, which abuts the Northern Territory/Queensland border. Phosphate occurs in the Cambrian Border Waterhole Formation in the Georgina Basin. The total Inferred Resource is 56 Mt at 16% P₂O₅ (at a 10% P₂O₅ cut-off). This includes 14 Mt at 20% P₂O₅ in the Western Mine Target Zone of the deposit. Following unsuccessful attempts to attract a strategic investor, the company have placed the project on hold and decommissioned the exploration camp.

Rox Resources Ltd announced results of drilling undertaken in late 2011 at the Marqua phosphate project in the southern Georgina Basin, east of Jervois. Drilling intersected high-grade mineralisation at a number of prospects along a 30 km strike length, with results including 3 m at 29.8% P₂O₅ from 45 m and 4 m at 28.6% P₂O₅ from 13 m (including 2 m at 34.2% P₂O₅) from Coquina Creek and 3 m at 16.2% P₂O₅ from 15 m at the Mauritania prospect.

Arafura Resources Ltd’s multi-commodity Nolans Bore orebody (see Rare earths) has Measured, Indicated and Inferred Resources totalling 47 Mt at 11% P₂O₅ for a total of 5.4 Mt of phosphate.

Potash

Rum Jungle Resources Ltd, in joint venture with Reward Minerals Ltd, have announced the Territory’s first potash resource at their Karinga Creek potash project, located between Erldunda and Curtin Springs along the Lasseters Highway, approximately 200–300 km southwest of Alice Springs. The Karinga Creek drainage system contains hundreds of salt lakes, representing the eastern extension of the Lake Amadeus system. The joint venture is investigating the potassium- and magnesium-rich brine resources for their potential as a feedstock for the production of sulfate of potash (SOP; potassium sulfate) and potassium magnesium sulfate (schoenite). Following the release of a maiden 530 000 t potash resource in May 2012, an upgraded resource was announced in November, with a maximum inferred resource of 5.5 Mt of SOP at an average aquifer thickness of 15 m and an average depth to the water table of 1 m. This equates to a maximum schoenite resource of 13 Mt. The average potassium grade from the 20 lakes in the resource is 4600 mg/l (at 3000 mg/l cut-off). The joint venture believes that the brine resource is sustainable and rechargeable for an extended period, with the potential to provide a long-term

Figure 8. Barrow Creek-1 phosphate deposit, showing high-grade phosphate within a few metres of the surface.
supply of potash salts. Two distinct aquifers are present, with one contained in unconsolidated near-surface lake sediments, and the second aquifer hosted in siltstone and sandy interbeds of the Devonian Horseshoe Bend Shale of the Finke Group (Amadeus Basin). The Horseshoe Bend Shale forms basement to most lakes, and where it is fractured, it contains free-flowing brine, leading Rum Jungle Resources to interpret that this is the aquifer that supplies most of the recharge water to the salt lake system. The company considers that groundwater flowing towards the Karinga Creek lakes leaches potassium, magnesium and sulfate salts from the basement rocks and then concentrates the brines through evaporation just beneath the lake surface.

**Salt**

Tellus Holdings Ltd (Tellus) announced in March 2012 that it hopes to develop an underground rock salt mine at their Chandler project near Titjikala, in the Amadeus Basin about 120 km south of Alice Springs. Interpretation of existing drilling and seismic data for the area has identified a potential salt resource within the Cambrian Chandler Formation, with a conceptual JORC Exploration Target of 4.0–4.8 Bt of halite at the main Mount Charlotte site. The Chandler Formation in the project area is interpreted to occur as a flat-lying, extensive evaporite unit (in excess of 200 m thick), with a variable halite mineralisation content that ranges from a 60–80 m-thick massive halite bed grading 80–95% NaCl to a 150–170 m thick succession of semi-massive halite beds with interbedded siltstone and anhydrite and an estimated grade of 30–40% NaCl. More drilling is required to more accurately determine the thickness and grade of the halite if it is to be brought to JORC Resource status. The deposit is also believed to contain magnesium and potash. Should the project go ahead, it would produce high-quality rock salt, or halite, which would be processed on site, trucked to the nearby railway line and mostly exported to Asia, where edible and industrial salts are in demand for products such as chlorine, soda ash and water treatment. Once the salt is mined, the voids left behind could be used to store products such as archives, equipment and waste. Tellus lodged a Notice of Intent with the Northern Territory Government in November 2012.

**Uranium**

Ranger is a world-class uranium deposit hosted in the lower Cailhill Formation in the Pine Creek Orogen, close to the structural contact with the underlying Archaean Nanambo Complex. Existing Ore Reserves at Ranger are 27.69 Mt at 0.14% U₃O₈, and Mineral Resources are 127 Mt at 0.09% U₃O₈. During 2012, Energy Resources of Australia Ltd (ERA)'s Ranger Mine produced 3710 t of uranium oxide, a 40% increase from the 2641 t produced in 2011. Open cut mining at Ranger Pit 3 ended in November 2012, and in December 2012, ERA commenced backfilling of this pit. From December 2012, the source of feed for the mill will be stockpiled material, including some high-grade ore mined in 2012. In June 2012, the ERA board approved a $57M Ranger 3 Deeps prefeasibility study, evaluating the scope for a proposed underground mine, including 16 000 m of additional resource definition drilling (in additional to the 35 000 m of drilling already allocated to the decline project), an extension of the decline and the installation of a ventilation shaft. Construction of the Ranger 3 Deeps exploration decline commenced in May, and by the end of 2012, the boxcut was completed and backfilled, and 57 m of the decline had been constructed. The current Ranger 3 Deeps resource contains 10 Mt at 0.34% U₃O₈ for an estimated 34 000 t U₃O₈. According to ERA, exploration expenditure on the Ranger lease was $45M in 2012, up from $9M in 2011, comprising $34M for the exploration decline and $11M for surface exploration.

Western Arnhem Land continued to be an important focus for uranium exploration in the Northern Territory in 2012. Cameco Australia Pty Ltd have continued a significant exploration program in their Wellington Range project area, located near the north coast of western Arnhem Land. At AGES 2012, Cameco presented on the discovery of significant high-grade uranium mineralisation at their Angularli prospect. From 2008–2011, seventy-one diamond drillholes varying from 130 to over 500 m in depth were drilled within the Angularli prospect area, and locally intersected high-grade mineralisation, with a reported intersection of 20.2 m at 5.2% U₃O₈ (including 0.5 m at 27.8% U₃O₈). The uranium mineralisation intersected at the Angularli prospect is primarily associated with a post-Kombolgie Subgroup, north-northwest-trending reverse fault, and mainly occurs in the hangingwall of a structural zone that extends from the basement into the sandstone cover. Uranium mineralisation is hosted in altered amphibolite-facies metasedimentary and magmatic rocks of the Nimbewah Domain and is associated with intervals of intense brittle and brittle-ductile deformation. Mineralisation occurs texturally in the form of patches, veins, stringers and breccia matrix infill, consisting primarily of uraninite and pitchblende. Some minor mineralisation also occurs in proximity to a prospect-wide redox boundary, and minor instances of coffinite have been intersected in the footwall above the unconformity. No further results from exploration during 2012 have been released.

Uranium Equities Ltd announced that it had reached agreement to acquire Cameco's 60% interest in the West Arnhem Joint Venture by spending $2 million over 4 years, at which point Uranium Equities would assume 100% ownership of the project, which surrounds Uranium Equities' 100% owned Nabarlek mineral lease. Uranium Equities also undertook a reconnaissance drilling program at their Headwaters project in southwestern Arnhem Land, which failed to intersect significant mineralisation. Alligator Energy Ltd continued to actively explore their Tin Camp Creek project, south of Nabarlek, undertaking 10 991 m of drilling during the year. In April 2012, Alligator Energy announced a maiden JORC-compliant resource for the Caramal deposit of 0.94 Mt
at 0.31% U$_3$O$_8$ for 2950 t of contained U$_3$O$_8$. Uranium mineralisation at Caramal is associated with strongly chloritised meta-arkose of the lower Cahill Formation, with strong geological similarities to mineralisation at Ranger and Jabiluka. Late in 2012, Alligator undertook drilling to test extensions of the Caramal resource, reporting intersections that included 15 m at 0.44% U$_3$O$_8$ from 75 m, immediately north of a fault zone that had defined the northern margin of the existing resource, and 15 m at 0.30% U$_3$O$_8$ from 130 m, at the eastern end of the deposit. Drilling immediately south of the existing resource intersected 23 m at 0.15% U$_3$O$_8$ (including 12 m at 0.23% U$_3$O$_8$). Alligator consider that the results of the extensional drilling provides sufficient encouragement to justify a more systematic drill-out at Caramal in 2013. Also during 2012, the company undertook a regional drilling campaign along the Orion trend that extends north and south of Caramal. Highlights included 32 m at 678 ppm U$_3$O$_8$ from 20 m (including 8 m at 0.11% U$_3$O$_8$), 70 m along strike from the original South Horn prospect, and 15 m at 512 ppm U$_3$O$_8$ from 78 m (including 5 m at 0.13% U$_3$O$_8$) in a complex structural zone of intense alteration at the Mintaka prospect, between Caramal and South Horn. The drilling program also identified additional broad zones of alteration and uranium anomalism that have been interpreted to reflect regional alteration systems. Alligator also discovered mineralisation at surface at the Orion East prospect, north of Caramal, with numerous rock-chips assaying in excess of 1% U$_3$O$_8$, and a maximum assay of 2.1% U$_3$O$_8$. The anomalous uranium rock-chips occur close to the interpreted contact between Archaean basement and the lower Cahill Formation.

UXA Resources Ltd undertook a second phase of drilling at their Nabarlek North tenements, with 21 holes drilled for 1740 m. Five of the eleven holes intersected elevated uranium values (from gamma logging) with strong sericitic, chloritic and haematitic alteration, and assays are pending.

Thundelarra Exploration Ltd (Thundelarra) continued to explore for both uranium and copper at its Allamber uranium project, 36 km north-northeast of Pine Creek. The project has a near-surface Inferred Resource of 1.4 Mt at 304 ppm U$_3$O$_8$ at the Cleos, Twin and Dam prospects, which were discovered by Total Mining Australia Pty Ltd in 1983. At Cliff South, three holes were drilled in 2012, which intersected broad zones of uranium mineralisation, including 23 m at 0.13% U$_3$O$_8$ from 86 m and 19 m at 821 ppm U$_3$O$_8$ from 98 m. These intersections also contained highly anomalous copper. No significant work was reported at Thundelarra’s Hayes Creek uranium project in 2012.

Energy Metals Ltd have continued evaluating the Bigrlyi uranium deposit in the Mount Eclipse Sandstone of the northern Ngalia Basin. The 2011 resource for Bigrlyi contains total Indicated and Inferred Resources of 7.5 Mt at 0.13% U$_3$O$_8$ and 0.12% V$_2$O$_5$ at a 500 ppm U cut-off, for 9600 t (21.1 Mlb) of U$_3$O$_8$ and 8900 t of V$_2$O$_5$. The Bigrlyi mineralisation remains open at depth and along strike. The results of a pre-feasibility study on Bigrlyi were released in mid-2011, and although they suggested that the project was technically feasible, an important finding was that a substantial increase in the resource base was required to improve project economics. A regional drilling program late in 2012 targeted Anomaly 15 East and Camel Flat, with assays pending. Energy Metals also reported success in the application of geophysical techniques to map prospective stratigraphy and mineralisation under thin transported cover.

Thundelarra Exploration Ltd’s Ngalia project includes significant palaeochannel-hosted uranium mineralisation in channels overlying the Ngalia Basin, including the 2010 Afghan Swan discovery. Mineralisation occurs along a package of grey, unconsolidated channel sediments at the base of the Cenozoic succession. Drilling in 2011 identified significant uranium mineralisation (greater than 100 ppm eU$_3$O$_8$) over a 15 km strike extent within the one palaeovalley system that has been tested, including a best intersection of 7.1 m at 0.14% eU$_3$O$_8$ from 135 m. No significant exploration occurred on this project in 2012.

Paladin Energy Ltd have assumed the role of operator of their joint venture with Cameco Australia at the Angela uranium deposit, 25 km south of Alice Springs, which has a resource of 10.7 Mt at 0.13% U$_3$O$_8$, for 13 980 t U$_3$O$_8$ (30.8 Mlb U$_3$O$_8$). No drilling was undertaken at the project in 2012.

**Onshore petroleum**

The Territory has seen an unprecedented level of onshore petroleum activity during the past year, with much of it due to an increased interest in unconventional petroleum, such as shale oil and gas, and basin-centred gas. Figure 9 shows petroleum tenure and basins, and the location of wells drilled in 2012 in the NT.

**McArthur Basin**

Armour Energy Ltd have a significant landholding in the southern McArthur Basin and northern Georgina Basin, and commenced trading on the ASX in April 2012. Most of Armour’s exploration in the Territory in 2012 was focused on the Batten Fault Zone, in the McArthur Basin near Borrooloola, with expenditure of $19.57M during 2012. In May 2012, they completed 56 line km of 2D seismic in the Abner Range area. Armour’s first well, Cow Lagoon-1, 25 km north-northwest of the McArthur River, was drilled to 1804 m depth, targeting a four-way dip closure. The well encountered gas flares and shows at several levels from 295 to 1560 m depth; gas was discovered in the Lynott and Reward formations with further gas shows in the Barney Creek and deeper formations on the Cow Lagoon West Anticline. A second well, Kilgour North-1 was drilled in June-July, but was suspended at 1142 m due to repeated water inflows. A third well, Glyde-1, located 61 km south of McArthur River, was spudded in late July and was drilled to a total depth of 698 m. The well intersected a continuous vertical section of 132 m of black, gas-charged, naturally-fractured Barney Creek Formation before intersecting the Coxco Dolostone Member. A highly deviated lateral
Figure 9. Map of Geological Regions of the Northern Territory showing granted petroleum permits as of December 2012, along with wells referred to in the text as being drilled or tested during 2012.
The Beetaloo Sub-basin is a significant depocentre of Mesoproterozoic Roper group sedimentary rocks that underlies the Mesozoic Carpentaria Basin in the area east of Dunmarra. In 2011, Falcon Oil and Gas Ltd signed a farm-in agreement with Hess Australia (Beetaloo) Pty Ltd (Hess), an affiliate of Hess Corporation, under which Hess can acquire a 62.5% interest in 25 200 km² of tenements in the Beetaloo Sub-basin, by conducting an extensive seismic program and drilling five wells. During 2012, Hess undertook 2D seismic in the Beetaloo Sub-basin, with 3600 km of planned seismic program, and were on target to complete it by the end of the year. Under the farm-in agreement with Falcon Oil and Gas, Hess must exercise its option to drill five exploration wells no later than 30th June 2013.

Georgina Basin
Petrofrontier Corp. is a TSX-listed company with extensive landholdings to explore for conventional and unconventional oil and gas in the southern Georgina Basin. In June 2012, PetroFrontier entered into a binding farm-in agreement with Statoil Australia Oil and Gas AS, a subsidiary of major Norwegian energy company Statoil, in which Statoil can farm-in to PetroFrontier’s exploration permits and applications in the Northern Territory by funding $195M of a total of $230M in exploration until 2016, to earn 56.3% of the project. During 2012, PetroFrontier drilled and hydraulically stimulated a number of wells in the southern Georgina Basin. The first horizontal well, Baldwin-2Hst1 was drilled in 2011 and reached a total measured depth of 1948 m. Positive hydrocarbon indications were recorded along the entire length of the horizontal section. A nine-stage hydraulic stimulation was successfully completed at MacIntyre-2H, but the well was suspended following the detection of traces of biogenic hydrogen sulfide gas. The third horizontal well, Owen-3H was drilled to 2153 m, of which the horizontal section was 966 m targeting the lower Arthur Creek Formation and Upper Thorntonia Limestone. Although fluid in core from Owen-3 seeped oil, no significant hydrocarbons were recovered during 20 days of testing of Owen-3H.

Amadeus and Pedirka basins
In late 2011, Central Petroleum Ltd announced a significant oil flow from the Surprise-1 re-entry well in the western Amadeus Basin, which was drilled to a depth of 2672 m. At the base of the lower Stairway Sandstone, the well encountered approximately 28 m true vertical depth of continuous fair to good oil shows, and inclusive of discontinuous shows, a total of 68 m true vertical depth of oil was discovered. The company then drilled a 230 m lateral well through the sandstone, with almost the entire interval encountering good to excellent oil shows. Initial flow testing of the well in January 2012 recorded a sustained flow rate of 380 bbl/day of light sweet crude oil. This is the first significant oil flow from an onshore discovery well in the Northern Territory in almost fifty years. An extended production test (EPT) resulted in first oil flowing in June and with 4560 bbl being produced in the September quarter. The EPT flowed stabilised rates of between 200–400 bbl/day without pumping, and the company is anticipating that substantially higher flow rates could be achieved if production commences. Water content remained below 10% and had reduced to 3.2% by the end of the EPT. A 82 km² 3D seismic survey was completed over the Surprise structure in July, and early reserve potential work suggests that the scale of the structure could support several production wells.

In the northern Pedirka Basin, Central Petroleum undertook a 96 line km 2D seismic survey in the Palaeozoic Warburton Basin to evaluate the Pellinor lead that involves a play associated with interpreted carbonate reefal facies.

Central Petroleum also announced a major farm-in agreement worth up to $150M with Santos Ltd for an 80 000 km² area in the Amadeus and Pedirka basins. Under the agreement, Santos will fund an initial $30M in exploration, with options to invest in two more stages worth $60M each, to earn rights of up to 70% in the area. Santos will assume operatorship of the tenements. Central Petroleum’s EP 115, which covers the Surprise oil discovery, is excluded from the joint venture.
Highlights from recent NTGS geoscience programs

Dorothy F Close,1,2 and Ian R Scrimgeour1

Current and previous Northern Territory Government precompetitive geoscience initiatives are designed to stimulate exploration through a range of strategies, including improving the quality and accessibility of the geoscientific data and knowledge of the Northern Territory by the Northern Territory Geological Survey (NTGS). The Regional Prospectivity group within NTGS is tasked with undertaking projects that achieve this objective. During 2012, a restructure of this group was delivered to improve its efficiency and effectiveness. The restructure has four geoscientific theme-based components: (1) Basin geoscience; (2) Basement Geoscience; (3) Geophysics and Remote Sensing; and (4) Commodities and Territory Wide. Each is headed by a manager who is accountable for delivering projects committed to under the individual themes and who is also the first point of contact for any enquirers.

Geophysics and Remote Sensing program

Eastern Amadeus Gravity Survey

During 2012, NTGS undertook a major gravity acquisition project over approximately two-thirds of the Neoproterozoic to Palaeozoic Amadeus Basin in central Australia. The Amadeus Basin is the focus of the Central Oz Basins Resource Assessment (COBRA) joint project with CSIRO and the enhanced gravity dataset has been incorporated into modelling of the basin architecture (Foss et al. 2013). The acquisition area covers the eastern section of the Amadeus Basin (Figure 1), extending to the South Australian border to encompass portions of the Mesoproterozoic Musgrave Province. A total of 7560 stations over an area of 102 160 km² was acquired during this project at 4 km grid spacing. USI NT Pty Ltd and Globe Mineral Resources Investments Pty Ltd supplied an additional 1175 infill stations at 1 km and 2 km spacing over specific tenement areas. These extra data were incorporated into the regional survey and are included in the available dataset. Images of the Eastern Amadeus Gravity Survey are available through the Geophysical Image Web Server (GIWS: www.geoscience.nt.gov.au/giws) via the NTGS website (www.nt.gov.au/dpifm/Minerals_Energy/Geoscience). The gravity data can be requested through the Minerals and Energy InfoCentre (geoscience.info@nt.gov.au) or downloaded via the Geophysical Archive Data Delivery System Application (GADDS) through the Geoscience Australia website (www.geoscience.gov.au).

National Virtual Core Library Project – HyLogger

The National Virtual Core Library (NVCL) is a collaborative project funded by the Commonwealth Government’s National Collaborative Research Infrastructure Strategy (NCRIS). The project is one component of an earth sciences platform managed through AuScope Ltd and implemented by CSIRO and all State and Territory geological surveys.

The original objective of the NVCL project was to progressively build a high-resolution hyperspectral and digital image of earth materials and properties for the upper one to two kilometres of the Australian continent. This was to be achieved through the scanning of drill core and cuttings held by the State and Territory geological surveys, using the purpose built HyLogger™ instrument.

Since delivery of the HyLogger in February 2010, over 60 000 m of core has been scanned from 180 holes across the Territory. Initial scanning focused on the NVCL aim of characterising the mineralogy of the top 1–2 km of the Australian crust by scanning deep holes from various terranes across the NT. The focus has now moved to more ‘project-based’ scanning. This includes the scanning of 51 drillholes from the Ngaïlia Basin, as part of a regional basin-wide study (Smith et al. 2012), extending upon the CSIRO JSU Ngaïlia Basin Uranium Mineral System Project study (Schmid et al. 2012). A ‘Tennant Creek Spectral Library’ has also been compiled, which characterises the spectral characteristics of typical rock-types and alteration assemblages from the Tennant Creek Mineral Field (Smith et al. 2013). A project to recognise and document the distinctive spectral responses to rare earth elements by characterising three different rare earth deposits from across the Northern Territory is currently underway (Smith and Huntington 2013).

Routine scanning of drill core from the Amadeus Basin, held in the NTGS Alice Springs Core Facility has commenced with results incorporated in the COBRA collaborative project between NTGS, CSIRO and exploration companies. In addition, all drillholes from the Geophysics and Drilling Collaborations are analysed through the HyLogger.

ASTER Geoscience maps of the Northern Territory

A series of 16 Territory-wide mineral index maps, generated using data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), was released in May 2012. The NT ASTER maps were produced through a collaborative effort between NTGS and the Centre of Excellence for 3D Mineral Mapping (C3DMM), and was led by the CSIRO’s Minerals Down Under Flagship with funding from NTGS. The ASTER mineral maps provide Territory-wide information on the distribution of the dominant rock- and soil-forming minerals in the Territory and provide an improved characterisation and understanding of the Territory’s geology.

The NT ASTER mineral maps have been made available in ECW format for viewing through NTGS’s Geophysical Image Web Server, and a complete dataset, including ECW, TIF, JPG and BSQ data, is distributed through NTGS’s InfoCentre. Following the release of the maps, CSIRO
Figure 1. Gravity images of Amadeus Basin before (a) and after (b) Eastern Amadeus Gravity Survey acquisition program. Black dots show gravity station coverage.
established stratigraphic correlations between the various tectonothermal events across the region, and has definition of the extent of the various overprinting Edition ALCOOTA mapsheet provides an improved unrecognised mineral systems.

A further objective is to highlight the prospectivity of structural and magmatic evolution of the Arunta Region.

with current knowledge of the stratigraphic, metamorphic, COBRA – Amadeus Basin project

The Central Oz Basins Resource Assessment (COBRA) project is a collaboration between CSIRO and the Northern Territory Geological Survey, aimed at assessing the mineral and unconventional hydrocarbon potential of central Australian sedimentary basins by applying new technology and systems thinking from hydrocarbon and minerals research. The project is designed to improve the understanding of the basin architecture, identify geochemical vectors to exploration and provide a link between depositional environments within basins and hydrocarbon and mineral systems (Schmid 2013). The first phase of this initiative is an analysis of the Neoproterozoic to Palaeozoic Amadeus Basin and includes industry partners Central Petroleum Ltd and Globe Mineral Resources Investment P/L.

Regional gravity data from the Eastern Amadeus Gravity Survey, acquired by NTGS, has been integrated into a 3D geophysical model, designed to improve the understanding of the structural architecture of the Amadeus Basin (Foss et al 2013). In 2013, NTGS will commence a 1:100 000-scale mapping program in HENBURY3 and RODINGA to investigate the Neoproterozoic stratigraphy of the Amadeus Basin.

Basement Geoscience program

Arunta Region

Since 2007, NTGS’s long-term commitment to improving the understanding of the framework and prospectivity of the Arunta Region has focused on the central and eastern parts of the region. The main objectives of this work are to provide updated hardcopy and digital maps at 1:250 000 and 1:100 000 scales from this area and to integrate these maps with current knowledge of the stratigraphic, metamorphic, structural and magmatic evolution of the Arunta Region. A further objective is to highlight the prospectivity of the region by identifying and characterising previously unrecognised mineral systems.

In the central Arunta Region, the newly released Second Edition ALCOOTA mapsheet provides an improved definition of the extent of the various overprinting tectonothermal events across the region, and has established stratigraphic correlations between the various metasedimentary units. The potential for base metals and copper-gold mineralisation north of a major structural feature, the Delny Shear Zone, has been highlighted, as has the prospectivity of uranium, lode gold and mafic-hosted nickel and vanadium mineralisation. A study undertaken on the geology and mineral potential of high heat-producing granites that host documented uranium and rare earth element occurrences within the NAPPERBY mapsheet has identified a potentially important regional mineralising event. An integration of field mapping and detailed geochemical and geochronological analyses of the Wangala and Ennugan Mountains granites has showed that although these granites have different ages (1775 Ma and 1620 Ma, respectively) and are separated by more than 50 km, they were both affected by a major fluorine-rich fluid-flow event at 1575 Ma, which led to metasomatism and localised rare earth element and uranium mineralisation (Beyer et al 2012a, b).

The Eastern Arunta project is designed to upgrade geological knowledge and to highlight the prospectivity of the eastern Arunta Region, with work to date focusing on the QUARTZ and LIMBLA mapsheets. The project involves new 1:100 000-scale mapping and geoscience programs, and the integration of historical data into a comprehensively revised framework and prospectivity assessment for the area. NTGS work in this area has stimulated extensive exploration company interest and has resulted in an increase in exploration expenditure in an area that had previously received little attention. In addition to a fundamental revision of the geological framework of the area, NTGS work has contributed to the discovery and characterisation of new mafic rock-hosted mineral systems (eg Basil Ni-Cu, Blackadder Cu-Co) and a new iron-oxide copper-gold province (Illogwa IOCG; Whelan et al 2012, Whelan et al 2013).

Geochronology

Geochronology forms an important component of most NTGS regional geoscientific projects. Through current NT Government funding initiatives, geochronological data have been acquired through the NTGS-GA Geochronology Project and through NTGS’s own geochronology programs.

The NTGS-GA Geochronology Project is a collaboration under the National Geoscience Accord, under which Geoscience Australia analyses samples from NTGS projects, with funding contributed from NTGS. As part of this program, rock samples have been dated using the SHRIMP (Sensitive High Resolution Ion MicroProbe) U-Pb method on the minerals zircon and monazite, with the results fully interpreted by Geoscience Australia. NTGS has undertaken further geochronological investigations using Laser ablation techniques to analyse U-Pb, Lu-Hf and O on zircons. All analyses undertaken through the NTGS-GA joint project and under NTGS’s project are routinely interpreted and reported in NTGS Records. A spatial layer with all U-Pb analyses reported in published NTGS Records is now available through NTGS’s online web mapping system, STRIKE.

3 Names of 1:250 000 and 1:100 000 mapsheets are shown in large and small capital letters respectively, eg HENBURY, LIMBLA.
Commodities and Territory Wide

Diamond commodity study

A major study was undertaken in 2009–2011 to provide a complete diamond exploration database and diamond prospectivity analysis for the NT, with the final products being released during 2012. The existing Diamond Indicator Mineral Database was extensively updated by including exploration data that had become available since the last update in 2005, including additional historical data missing from the previous database, and by expanding the data fields to include a number of additional criteria important for exploration. The updated and expanded database includes many thousands of new sample sites, and formed the basis for a subsequent prospectivity analysis.

The upgraded Diamond Exploration Database for the Northern Territory was released as NTGS DIP009 and includes an expanded range of fields for each data location. The database incorporates the locations of over 75,000 diamond exploration samples (Figure 2), the overwhelming majority being samples taken for the separation of diamonds and diamond indicator minerals. Associated with these samples are over 14,500 chemical analyses of mineral grains, acquired during the course of diamond exploration. The upgraded database now includes:

Figure 2. Diamond prospectivity map of the Northern Territory (after Hutchison 2012).
• bulk geochemical sample locations relevant to diamond exploration
• trace element mineral chemistry
• application of contemporary discrimination models to indicator mineral chemistry
• background mineral chemistry to provide a context for exploration
• background mineral recovery to provide a platform for commodity diversification
• references to relevant geophysical surveys
• copies of diamond-positive company reports, and integration of non-company report data.

The database is presented in a GIS-integrated fashion and with accompanying explanatory documentation.

The second major product to come from this study is NTGS Record 2012-001, Diamond exploration and prospectivity of the Northern Territory, released in July 2012 (Hutchison 2012). This report includes a review of known diamond and kimberlite occurrences in the Territory, a review of past exploration, and a comprehensive diamond prospectivity assessment.

Murphy Inlier

An NTGS project is being undertaken to assess the mineral potential and to provide a geological framework for mineral exploration in the Murphy Inlier region (Murphy Province), adjacent to the Queensland border in CALVERT HILLS. The project was designed to better understand and subdivide the stratigraphy of the Murphy Inlier, and to assess the known mineral systems and mineral potential of the area, which has a significant copper, uranium and gold endowment. A study into the Seigal Volcanics (Orth 2010) documented a regional-scale potassic alteration system, suggesting that this formation is an attractive target for uranium and copper mineralisation. Preliminary fluid inclusion data indicate that uranium and copper in the Murphy Inlier area were transported by fluids with similar physicochemical characteristics, indicating potential for the presence of a single uranium–copper mineralising system.

Base metals deposits of the NT

A comprehensive review of the base metals deposits in the Northern Territory commenced in 2009 (Khan 2012). An NTGS Report, Base metals deposits of the Northern Territory, is due for release in 2013 and will be the first major NTGS publication detailing the copper, lead, zinc and silver deposits of the NT.

Mafic rocks of the NT

A project to assess the economic and tectonic significance of mafic rocks within the Northern Territory is in progress, with a particular focus on central Australia. It has been designed to: (a) identify rock units largely comprising, or hosting substantial mafic and ultramafic rocks that may be associated with mineralisation (particularly nickel-copper, platinum group elements and vanadium magnetite); and (b) to use petrogenetic interpretations of mafic and ultramafic rock units to contribute to an understanding of tectonic environments. A key component of this project is to develop a standardised NTGS approach to the collection and interpretation of relevant geochemical, isotopic, petrographic and field data, to ensure a consistent approach to the interpretation of mafic rock units.

Initial areas that have been targeted under this project include the eastern Arunta Region, the Davenport Province of the Tennant Region and the eastern margin of the Musgrave Province. An NTGS Record documenting the standardised collection and interpretation techniques applied in this project is in preparation with subsequent terrane-based reports to provide analyses of the mafic units within specific Proterozoic provinces within the NT.

Geology and mineral resources of the Northern Territory

A major focus for NTGS over the past year has been on finalising NTGS's flagship publication, entitled Geology and mineral resources of the Northern Territory. This volume is intended to be the first point of call for all information on the geology and resources of the Territory (Figure 3) and will be approximately 1100 pages in length, containing 42 chapters. It is a technical publication targeted primarily at mineral and petroleum explorers, and will be released as a case-bound book, as a CD, and online.

Figure 3. Cover of NTGS Special Publication 5, Geology and mineral resources of the NT.
The project has necessitated a thorough review of NTGS’s understanding of the geology and mineral resources of the whole of the Northern Territory, and has led to important revisions of the geological regions subdivision and first-order geological framework of the Northern Territory. This is the first-ever compilation of the Territory’s geology and mineral resources in a single volume and it includes the first modern summaries of the geology and resources of a number of basins and provinces. The hardcopy release of the publication will occur by June 2013.

Geophysics and Drilling Collaborations Program

The Geophysics and Drilling Collaborations Program is a major component of the NT Government’s current precompetitive geoscience initiative. The program provides for co-funding of exploration drilling and geophysical acquisition projects, to a maximum of $100,000, in areas where there is a paucity of geoscientific data, and is designed to stimulate exploration in greenfields areas of the Northern Territory. Since the program’s inception in 2008, the first four rounds of funding has resulted in funding being awarded to

Figure 4. Locations of projects in Rounds 1 to 5 of Geophysics and Drilling Collaborations program. Open file company report numbers are included.
a total of 45 projects, of which 35 were wholly or partially completed. To enhance the geoscientific value of the drill core acquired through this program, all core is routinely scanned through the NTGS HyLogger instrument, with the acquired hyperspectral data, core imagery and resultant interpretation immediately open filed. The distribution of co-funded projects across the Northern Territory, through this program, is indicated in Figure 4.

During 2012, Round 5 of the Geophysics and Drilling Collaboration Program saw five drilling and five geophysical acquisition programs awarded co-funding. Two of these projects did not commence within the required timeframes, resulting in the withdrawal of co-funding. Projects completed in Round 5 have included the acquisition of over 3000 line km of TEMPEST airborne electromagnetic data over the Arunta Region and Wiso Basin (ABM Resources NL and Toro Energy Ltd), and nearly 2000 line km of magnetic and radiometric data at 200 m line spacing over the Daly Basin (Consolidated Global Investments Ltd).

Co-funded drilling projects in Round 5 included a deep drillhole (ca 800 m) by CKA Resources Ltd through the Georgina Basin succession to target a coincident gravity and magnetic anomaly in underlying, interpreted Tennant Region basement. Deep drillholes near Larrimah and southeast of Elliot by Western Desert Resources Ltd in Round 5 have the potential to further define the buried geology and prospectivity beneath the onshore Carpentaria Basin. This information should complement co-funded drilling from Round 4, undertaken earlier in 2012 by Natural Resources Exploration Ltd (NRE) in the Daly Waters area. NRE drilled a 317 m drillhole that revised the understanding of the subsurface geology, unexpectedly encountering 38 m of late Miocene to early Pliocene sands, with no Cretaceous Carpentaria Basin strata being intersected. The hole passed through limestone equivalent to the Georgina Basin and then into the shale of the McArthur Basin at 137 m depth. The shale locally contains minor copper as chalcopyrite and its identification at relatively shallow depths upgrades the prospectivity of this area for base metals.

Data and reports related to co-funded projects from Round 5 of the Geophysics and Drilling Collaborations program are either currently open filed or shortly due for public release. More information regarding the program, currently funded projects and the upcoming dates for Round 6 funding applications can be found at the Geophysics and Drilling Collaborations website: www.minerals.nt.gov.au/collaborations.

References


Improvements to data delivery and access to data continue to be a priority of NTGS. Another major upgrade to the STRIKE web mapping system was implemented in August 2012 that included all available data from the various Titles Registers and the complementary land information datasets. Improvements include nightly updates to the titles layers and a number of pre-defined search queries using the titles data.

A new database for the discovery of Core Sampling Reports will be launched at AGES. The reports covered by the database are those provided by NTGS collaborators and clients that are required when sampling drill core held by the NTGS Core Facilities. Users will be able to do a free text search across fields or search on a number of structured fields.

Other significant achievements in 2012 include the completion and release of the NT-wide ASTER mineral maps and dataset, the GIS dataset for the 1983 Alligator River 1:250 000-scale mapsheet, five new Records and the Eastern Amadeus Gravity Survey.

Web delivery systems – upgrades

To recap from 2012, STRIKE v2, launched in March 2012, has a completely new look and feel for the user interface and an ECW browser plug-in is no longer required to display imagery. The new version has also resolved some issues with the previous version, particularly compatibility with more recent versions of the Internet Explorer web browser. In August 2012 another significant STRIKE upgrade was completed, this time focused on content. All the titles and ancillary land management layers from the Titles Information System (TIS) were added to STRIKE to provide an alternative discovery and display interface for those clients having browser compatibility issues with TIS. Although without the full functionality of TIS, clients can search for Titles Register information, and display and download data, including title holders. The title layers on STRIKE are now updated every night and are the most up-to-date title data available. With the addition of the new layers, new pre-defined searches are now available for clients, including Titles by holders, Titles by number, Drilling by current title, Historic mineral titles by current title (to find open file reports easily) and Seismic lines by current EP.

A new bibliographic database, Core Sampling Reports (CSR) will be launched at AGES. The reports covered by the database are those provided by NTGS collaborators and clients that are required when sampling drill core held by the NTGS Core Facilities. Clients will be able to search on subject terms, drillhole ID/reference, author/sampling organisation, the original tenure when the core was collected, stratigraphic unit and geological province, as well as in free text fields such as title and abstract. Each record cross-references the relevant CoreDat ID numbers, so that further information on the sampled core can be accessed. Copies of the reports can be requested from the InfoCentre. In the longer term, there are plans to make the full text reports available online.

An online NTGS product catalogue database was launched in March 2012 just prior to AGES. Users are able to search for relevant products using any word or by a particular element, such as geological province and product type. The product catalogue also includes records on individual AGES abstracts to enable users to find all useful references on an area. Over the last year, a considerable effort has been put into ensuring that all currently available products are downloadable from the catalogue, except for those of a large size, eg geophysical data. Clients should be aware that information on the NTGS unpublished report collection is not in the product catalogue, but can be found in the Minerals and Energy InfoCentre Library Catalogue. These reports are not downloadable.

Reporting under the Mineral Titles Act 2010

With the introduction of the new Mineral Titles Act 2010 and a stronger focus on compliance with reporting requirements, the number of reports rejected for non-compliance has risen. Common reasons for rejection include non-compliant data formats, incorrect or insufficient information on the title page, and the lack of a conclusion and recommendations in the report. The most common error with the submitted geochemical data is missing laboratory methods and assay detection limits, and while there have been improvements in geophysical data submission, some data is still not submitted in GDF2 format. About 10% of reports in 2012 were rejected and initiated a formal letter requesting resubmission. This number is expected to drop over time as clients become more familiar with the guidelines and streamline their internal reporting processes. Amalgamated or group reporting has increased and use of the group report (GR) number in file naming ensures better identification and management of amalgamated reports.

Mineral production data is now collected under the new Act on an annual basis. Data is collected for the financial year period and a summary is available on the website www.minerals.nt.gov.au, under the Information and Services link on the left hand menu.

NTGS products, spatial data and client services

The NT-wide ASTER mineral maps and dataset, and the Eastern Amadeus Gravity survey were completed and released in May and September 2012, respectively. New editions of the NT-wide gravity map and metallogenic maps will be released at AGES in March.

Introduction

ABM Resources NL (ABM) is a Perth-based company exploring in the Tanami and Arunta regions of the Northern Territory. Since 2010, ABM has shown its commitment to grassroots exploration, discovery-stage and resource delineation through work on gold-focused projects in the Tanami–Arunta regions. ABM is one of the largest exploration license holders in the NT (and in Australia) and has demonstrated a tiered approach to exploration.

Following acquisition of former Newmont-held ground in 2010, ABM advanced discovery at the Twin Bonanza camp, comprising the Old Pirate and Buccaneer prospects, and released a Maiden Inferred Resource (1.67 Moz Au) for the Buccaneer system in early 2011. Work is ongoing to further define and evaluate this project, and in 2012, the resource was upgraded to 2.67 Moz (Inferred and Indicated). Following excellent surface sampling and drilling results, the company’s focus moved to the Old Pirate project, where a maiden resource of 427 400 oz was announced in 2012. A focus on extension and infill at Old Pirate continued through 2012 and an upgraded resource estimate was released in February 2013, comprising 611 000 oz (inferred and indicated), representing a 43% increase. ABM is now moving the Old Pirate deposit into a development phase.

ABM’s ‘drill early, drill deep’ strategy reflects an aggressive and active exploration mindset, in which the company uses field mapping and geochemical sampling to build on geophysical data and tectonic frameworks, in order to target large mineral systems that could support a stand-alone development.

Twin Bonanza Gold Camp

Background

The Twin Bonanza Gold Camp is centred approximately 20 km south of the Tanami Road and 15 km east of the Northern Territory/Western Australia border. It comprises the Intrusion Related Gold System (IRGS) at Buccaneer and the high-grade vein system at Old Pirate. The Buccaneer IRGS is an 1802 ± 8 Ma porphyritic syenogranite intruded into Wilson Formation sandy turbidites of the Ware Group. In 2012, ABM announced an upgraded Inferred and Indicated Resource of 127.9 Mt grading 0.65 g/t for a total of 2.67 Moz gold (0.2 g/t cut-off). The resource extends over 600 m x 400 m of the southern portion of the 2200 x 900 m stock (Figure 1). In February, ABM announced a revised resource for Buccaneer, focused on localised high-grade zones. The 2013 resource supplements the 2012 resource. It represents an optimisation for higher grade within the 2012 resource volume, and comprises 515 300 oz at 2 g/t (top cut) of Inferred and 732 200 oz at 2.43 g/t (top cut) of Inferred material for an overall resource of 1 098 200 oz at 2.54 g/t Au (top cut).

The Old Pirate prospect contains high-grade, gold-bearing quartz veins hosted in sandy turbidites of the Killi Killi Formation of the Tanami Group. Two adjacent and parallel anticlinal sub-folds, approximately 50 m apart, occur at Old Pirate. Mineralisation is continuous, with gold endowed in antclinal and synclinal hinges, as well as along the entire length of the limbs. Trenching along these veins has so far determined a zone of multiple veins with a strike length exceeding 700 m at an average grade in excess of 20 g/t (Figure 2). In 2012, ABM announced the discovery of the Golden Hind vein, located 800 m south of the main Old Pirate mineralised body (Figure 2). Golden Hind represents a spatially limited zone with spectacular surface sampling and drilling results, including 42 m at 44 g/t Au from surface in GHRC100014.

Following continued surface sampling and drilling campaigns through the 2012 season, ABM announced an updated resource for Old Pirate in February 2013. The current resource comprises 993 000 t of Inferred material at an average grade of 11.8 g/t Au (300 g/t top cut applied) and 889 000 t of Indicated material at an average grade of 8.19 g/t Au (300 g/t top cut applied) for a total of 611 000 oz at an average of 10.1 g/t Au.
ABM intends to complete a 10 000 t mining trial at Old Pirate in 2013. Expanded trenching and trial mining is aimed at increasing the understanding of the geology, grade distribution, dilution management, thickness, orientation and mineralisation controls, as well as confirming the metallurgical characteristics, to ensure the ore is amenable to proposed gravity-only recovery. At the time of writing, permits to complete this work are pending grant.

Advanced Projects

Hyperion

Hyperion is located approximately 20 km NNE of the Groundrush gold deposit (Tanami Gold), and 60 km NE of the Tanami Mine (Tanami Gold). Following work by Zapopan, Otter, Acacia and North Flinders Mines, Newmont defined a consistent geochemistry anomaly, with samples collected over the Hyperion prospect in 2003. Follow-up RC drilling (Figure 3) further defined the project and delineated further prospects, including Hyperion South. Drilling on the tenement was continued by Newmont until 2005. Following a renewed drilling campaign in 2011, ABM published a Maiden Inferred Resource of 202 200 oz with an average grade of 2.11 g/t gold (0.8 g/t cut-off with 50 g/t top cut applied) in April 2012.

Barrow Creek Regional Project

The Barrow Creek Regional Project is a 160 km-long geophysical gravity trend located approximately 350 km NNW of Alice Springs in the western Arunta Region. The region has several known mineral occurrences including

Figure 1. Location and summary – Buccaneer.
gold, copper, nickel, zinc, tin and tantalum and includes
the Waldrons Hill, Harrison, Lennon, Eleanor, Tulsa and
Kroda prospects. The dominant rock types in this project
area include quartz-biotite schist and quartz arenite to the
north, interpreted to be part of the Gwynne Sandstone and
Illoquara Sandstone, along with tuffaceous siltstone and
arenite of the Strzelecki Volcanics (all formations within
the Wauchope Subgroup of the Hatches Creek Group). Minor granite intrusive rocks occur throughout the area. A
strong NW–SE foliation is observed in the region, parallel
to numerous quartz veins that define common NW-trending
ridges. Exploration during 2012 included reconnaissance
mapping, surface sampling (as described below), an airborne
EM survey and drilling.

The airborne EM survey also included the Reynolds
Range and Bonita projects for a total of 1159 line km, at
400 m line spacing at a nominal 100 m terrain clearance.
This project was, in part, co-funded through the NTGS
Geophysics and Drilling Collaborations program. Following processing, a total of 12 targets were selected
for drill testing. Of these, 6 targets were interpreted to
represent a semi-continuous linear conductor in the order
of 50 m wide, observed over a strike length of 2 km. Drill
testing of this target was completed late in 2012, comprising
8 RC holes for a total of 2234 m. Results revealed wide
intersections of pyrite with low-level but anomalous gold
and copper. The intersected stratigraphic succession
includes a sequence of quartz mica schist with andalusite
porphyroblasts, interpreted to be part of the Bullion Schist
(meta-turbidite sequence), intercalated with amphibolite
lenses, interpreted as meta-dolerite. Two phases of meta-
dolerite have been identified, with a different appearance
and multi-element response.

The Kroda Gold Project is located 18 km west of
the Stuart Highway, 30 km north of Barrow Creek and
200 km south of Tennant Creek. The project consists of
4 prospects (Kroda 1 to 4) with a combined strike length
of 14 km. In 2011, ABM completed a program of 15 holes
for an aggregate of 2490 m, confirming a second discovery
camp in the Northern Territory with results including 29 m
averaging 6.38 g/t Au.

2012 surface sampling results

The majority of the outcropping and sub-cropping gold-
bearing deposits in the Northern Territory have been
discovered and increasingly, explorers are looking for
buried deposits. Complex regolith profiles and transported
cover hinder these efforts.

There are numerous commercial surface geochemical
techniques that are aimed specifically at the detection
of deposits buried under cover with very low surface
geochemical signals. These techniques typically assume
some form of upward movement of ions through the cover,
changing the surface chemistry in some detectable fashion. Techniques include multiple weak leach techniques,
pH and conductivity surveys, and very low detection
laboratory assays. They all aim to detect mineralisation
that is covered by many metres of exotic cover and is
essentially ‘blind’ at surface.

Following successful orientation surveys completed
at Buccaneer in 2011, ABM conducted extensive Deep
Penetrating Geochemistry (DPG) surface sampling in
the wider Twin Bonanza, South Tanami, Bonita and
North Arunta project areas in 2012. The aim of these
DPG surveys was to enable the company to assess the
mineralised system potential of large areas, both rapidly
and cost effectively.

Beyond the Twin Bonanza area, ionic leach sampling
was undertaken within the Bonita Project (Bonita and
Swampy surveys), the Barrow Creek Project (Eleanor,
Tulsa and Lennon surveys) and over the South Tanami and
Mallie prospects (Figure 4).
**Twin Bonanza project area**

Sampling was completed at the Beam, Cannon, Jack-Sparrow, Nova, Rudder and Skullduggery prospects (Figure 5).

Results at Beam correlate well with known outcropping quartz veins, and indicate scope for semi-continuous extension of the veins to the NW. The main geochemical anomaly at Beam also includes a response extending 1.25 km to the SW of known quartz veins, with the anomaly then trending NW; this is interpreted to represent a fold closure. The geochemical response remains open to the NW. At Cannon, the geochemical response is patchy, but indicates scope for further mineralisation up to 1.5 km south of Golden Hind, on the trend of the Old Pirate axial plane. Results from the Jack-Sparrow survey are similarly patchy. The Nova survey shows an extensive zone of moderately to highly anomalous gold responses that remains partly open in the NE of the survey area.

![Figure 3. Drilling summary – Hyperion.](image1)

![Figure 4. Location of regional DPG programs, 2012.](image2)
South Tanami and Mallie project areas

The South Tanami sub-project is located approximately 540 km northwest of Alice Springs and is about 20 km west of the currently operating Callie Mine. Variable transported and platform cover, including the Antrim Plateau Volcanics, precludes a robust geological understanding in the South Tanami area. Geophysical features indicate the presence of the Palaeoproterozoic Dead Bullock Formation and overlying Killi Killi Formation. Several Palaeoproterozoic intrusions have been interpreted.

Mallie is located 30 km WNW of Callie, and exhibits similar geophysical characteristics to this world-class orebody. The Mallie survey is sited over an interpreted zone of interaction between the Tanami and Mongrel faults (and related splay), and includes historic anomalies generated by patchy drilling over a strong magnetic high. The Mallie survey (Figure 6a) returned some of the highest tenor results for the season, generating anomalies that correspond well with gravity and magnetic features, similar to those observed in the Callie area. It is likely that the geophysical anomalies represent a region of highly favourable geology and tectonic setting.

The South Tanami survey, 20 km west of Callie, was designed to provide geochemical understanding over an area that displays structural controls and geophysical responses analogous to the Callie setting. A small anomaly occurs on the southern extent of the area (Figure 6a), and indicates that the survey has detected the northern extent of the Officer Hill project which lies under variable Antrim Plateau Volcanics cover to the south. Results also indicate a 5 x 3 km zone with moderate gold response, supported by silver, copper and molybdenum, coincident with gravity and magnetic features that are similar to those at Callie.

Barrow Creek Project

Results from surface sampling programs at Eleanor, Tulsa and Lennon prospects are presented below.

The Lennon survey was designed to test the relationships between anomalous historic soil samples and tightly folded magnetic stratigraphy that is potentially bound by faults to the south. An elevated gold response at Lennon corresponds with magnetic features that suggest complex folding of magnetic strata (Figure 6b), and falls on the margin of a significant gravity high. These geophysical features are characteristic of Kroda to the southeast; however, the features at Lennon indicate that the degree of shearing may be reduced, giving scope for a broader exploration target.

The Eleanor survey area occurs within greenschist- to amphibolite-grade metamorphosed sandstone and siltstone of the Lander Rock Formation, with strongly magnetic units that are interpreted as dolerite. Historic sampling has generated several significant gold, arsenic and copper anomalies. Two significant multi-point anomalies have been generated by the Eleanor survey (Figure 6c). In the NW, a broad zone (7.4 x 6.2 km) of patchy moderate gold response remains open to the west. In the east of the area, a roughly north–south, 3 x 1.5 km zone with strong gold results was returned. Both anomalies also contain coincident elevated silver, arsenic, copper and zinc values.

The Tulsa prospect is situated 15 km WNW of the Kroda prospect. At Kroda, surface and drill sampling shows an extensive gold response on both the northern and southern flanks of an extensive, discrete, high-magnitude, linear magnetic high. Results from the Tulsa survey (Figure 6d) show that the gold response continues to the NW along strike of the Kroda magnetic feature, effectively extending the strike length of the Kroda system from 14 km (previously established) to 26 km.

Figure 5. Location of prospects – Greater Twin Bonanza area.
Bonita Project

The Bonita Project is located approximately 230 km north-northwest of Alice Springs. On a regional scale, the area has a very complex geology; polydeformed Palaeoproterozoic Lander Rock Formation metasedimentary rocks, which host gold mineralisation, are intruded by numerous felsic and mafic intrusive phases, and are overlain by slightly younger siliciclastic metasedimentary rocks, including the Reynolds Range Group. The area is covered by complex regolith, with scree shedding from substantial hills cut by large drainage systems.

Figure 6. Correlation of geochemical results (regional DPG surveys) and geophysical features; Mallie–South Tanami, Lennon, Eleanor and Tulsa surveys.
The Bonita survey was designed to test a conceptual target over a broad trend of regional magnetic features. The tenement has limited historic data, comprising 19 samples with a maximum gold result of 6 ppb in conventional soil sampling. Gold response is consistently elevated on the western margin of the current survey (Figure 7a), corresponding very well with localised magnetic features. There is a patchy gold response on the northern margin of the survey, but this does not correlate well with the magnetics.

Swampy is a conceptual target over a magnetic anomaly that has seen limited historic test work, comprising six aircore drillholes, varying from 45 m to 90 m in depth, which yielded a maximum gold assay of 0.026 ppm. The largest DPG anomaly generated at Swampy covers an area of approximately 7 x 2 km with a distinct NNW trend (Figure 7b).

This anomalous area corresponds with several NW–SE-trending, linear magnetic features, which suggests that gold in the area is spatially associated with stratigraphic units, potentially adjacent to a fold closure/hinge zone to the southeast.

2013 proposed program

The immediate focus for 2013 is the proposed bulk sample at Old Pirate; however, ongoing geological and geochemical surveys are also planned.

Twin Bonanza Project

At Old Pirate, numerous targets remain to be tested. These include targets to infill and extend the existing resource, such as northward extensions to the eastern and western limbs of the Old Pirate anticline, depth extension on the western limb and plunge extension in the anticline hinge. The company will also be exploring for small areas of high-grade mineralisation, such as Golden Hind.

Following analysis of drilling results, geological modelling and apparent structural controls, ABM geologists have generated conceptual targets that may lead to the discovery of new systems proximal to Old Pirate.

At Buccaneer, drilling will continue to focus on incremental additions to the resource. Recent work has highlighted the continuity of narrow, relatively high-grade structures within the overall system, and work will be completed to better target and understand these zones.

Regional Work

Regionally, ABM’s work will focus on a better understanding of the geological framework. Numerous poorly understood targets occur within a vast area. Existing geological and geochemical coverage is inconsistent and difficult to confidently interpret. Regional mapping, along with broadly spaced ionic leach soil geochemistry, is planned for the Lake Mackay, Barrow Creek, Reynolds Range, Bonita and Northern Tanami areas. By combining consistent geochemical, geological and geophysical datasets, ABM intends to develop a robust pipeline of drill targets within the Tanami Region.

Figure 7. Correlation of geochemical results (regional DPG surveys) and geophysical features; Bonita and Swampy surveys.
The Cu ± Au potential of the Arunta Region: Links between magmatism, tectonism, regional-scale alteration and mineralisation

Jo A Whelan1,2, Dorothy F Close1, Ian R Scrimgeour3, Eloise E Beyer4, Natalie Kositicin5 and Richard A Armstrong5

Introduction

The Arunta Region (Figure 1a,b) of central Australia has undergone a substantial increase in exploration for Cu ± Au mineralisation in the last five years, with the reporting of high-grade intersections and resources at historical prospects such as Jervois, Mount Hardy, Johnnies Reward and Home of Bullion (Scrimgeour 2013 and references therein), and new discoveries such as the Illogwa IOCG belt and Basil in the eastern Arunta Region (Figure 1a,b). The identification of regional-scale alteration systems that are similar to those associated with iron-oxide copper-gold (IOCG) mineralisation (Whelan et al 2011a, 2012, Beyer et al 2012) during NTGS mapping programs has stimulated exploration in areas previously underexplored for Cu, particularly in the southeastern Arunta Region. Furthermore, the acquisition of deep-crustal seismic data (Georgina–Arunta seismic traverse GA09-GA1; Korsch et al 2011) and associated prospectivity studies, undertaken by Geoscience Australia in conjunction with NTGS, have also shown the potential for the Arunta Region to host U-rich IOCG systems (Huston et al 2012). All of these studies and exploration results highlight the increasing greenfields potential for a range of Cu ± Au mineralisation styles in the underexplored Arunta Region.

Regional geology and known copper mineralisation styles of the Arunta Region

The Arunta Region is variably exposed over 200 000 km² in central Australia and forms part of the southern extension of the North Australian Craton (NAC). It is characterised by a remarkably protracted history, spanning almost 1.5 Ga, of sedimentation in varied environments, episodic deformation, moderate- to high-grade metamorphism and bimodal magmatism. The region comprises three provinces which have distinct protolith ages and histories: the Paleoproterozoic Aileron Province, Palaeo–Mesoproterozoic Warumpi Province and the Neoproterozoic to Palaeozoic Irindina Province (Figure 1a, Scrimgeour 2003). The Aileron and Warumpi provinces are partly covered by Neoproterozoic to Palaeozoic volcanic rocks that are time equivalents and in some cases, direct correlatives of units in the Tanami Province and the Davenport Province of the Tennant Region (Scrimgeour in press a). The majority of magmatism occurred in the interval 1820–1700 Ma and in the southeastern Arunta Region, the province is affected by what has been interpreted to be a Palaeoproterozoic convergent margin (Foden et al 1998, Zhao and McCulloch 2012a, b). Intrusive rocks in this area show a progression with time from dominantly mafic and felsic I-type magmas, derived from isotopically juvenile sources, to more felsic A- and S-type magmas, derived from isotopically evolved recycled Palaeoproterozoic, Neo- and Mesoarchaean components (Whelan et al 2011b, 2012a, b).

The Aileron Province has been affected by a number of events with varying spatial distributions and tectonic styles, including the 1810–1790 Ma Stafford Event, 1780–1770 Ma Yambah Event, 1735–1690 Ma Strangways Event, 1590–1560 Ma Chewings Orogeny and the 450–300 Ma Alice Springs Orogeny. Recent geochronological and petrological studies in the eastern Arunta Region have identified mounting evidence for a high-T, low-P tectonothermal event associated with voluminous, dominantly felsic magmatism during the interval 1750–1740 Ma (Whelan et al 2011a, 2012b, Kositcin et al 2011, 2013, Bodorkos et al in press, Whelan et al in pre a). Magmatic rocks emplaced during this event show intense alteration associated with Cu ± Au mineralisation in the newly identified Illogwa IOCG belt (Lyons et al 2013).

The Aileron Province is prospective for a number of styles of copper mineralisation, including the prospects shown in Figure 1b and briefly described in Table 1:

- Intrusion-related mineralisation (IOCG-style), such as Johnnies Reward and Gumtree in the Strangways Metamorphic Complex (Figure 1, Hussey et al 2006); base metals-Au deposits of the Jervois district that are hosted in the Bonya Schist (Lennartz 2012); and Austin,
Powers, Bigglesworth, Mini-Me and El Gordo of the Illogwa IOCG belt (Lyons et al. 2013), which are spatially associated with the ca 1750 Ma oxidised Atneequa Suite (Whelan et al. 2012a).

- Vein-hosted mineralisation, including Arthur Popes, which is also elevated in REE (Mithril Resources, ASX Announcement, 6 August 2007); the Pinnacles copper district, which is hosted in quartz-carbonate veins in the Cadney Metamorphics; and Hale River, which is hosted in quartz veins in the Illogwa Shear Zone.
- Shear zone-hosted deposits, such as Home of Bullion, which comprises four shear zone-hosted massive sulfide lenses within the Bullion Schist (Ferenczi 2005).
- Hydrothermal-related, such as Kongo, Copper Queen and Copper King (Scrimgeour in press a).

Only the intrusion related (IOCG) occurrences will be discussed in more detail below.

**Warumpi Province**

The Warumpi Province (Scrimgeour 2003) is an east–west-trending domain that extends along the southern margin of the Arunta Region (Figure 1a). It has been interpreted as an exotic terrane that accreted to the North Australian Craton at ca 1640 Ma (Scrimgeour et al. 2005b). The margin between the Warumpi and Aileron provinces is interpreted to be a strongly reworked suture (Central Australian Suture; Close et al. 2005) and is now defined as a series of faults and thrusts (including the Desert Bore Shear Zone and Redbank Thrust; Scrimgeour in press b). The Warumpi Province

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**Figure 1.** (a) Schematic regional geological map of Arunta Region, showing division of provinces. (b) Schematic regional geological map of Aileron Province showing locations of Cu-Au occurrences and distribution of ca 1770, 1750 and 1567 Ma intrusive rocks.
### Summary of Cu ± Au occurrences in Aileron, Warumpi and Irindina provinces.

<table>
<thead>
<tr>
<th>Style</th>
<th>Deposit [commodity]</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Aileron Province</strong></td>
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<tr>
<td>Intrusion-related IOCG (?)</td>
<td><strong>Johnnie's Reward</strong> [Cu-Au-(Pb-Zn-Ag)]</td>
<td>Cu-stained massive ironstone with quartz-garnet-biotite gneiss hosted in Strangways Metamorphic Complex</td>
<td>Hussey et al (2005), Scrimgeour (2013)</td>
</tr>
<tr>
<td></td>
<td><strong>Perenti</strong> [Cu-Au]</td>
<td>Chalcopyrite, pyrite and haematite in quartz-fluorite-haematite-chlorite veins cross-cutting sheared, locally brecciated and red rock-chlorite-altered biotite granite.</td>
<td>Ivanac (1970), this study</td>
</tr>
<tr>
<td></td>
<td><strong>Mount Hardy</strong> [Cu-(Au-Pb-Zn)]</td>
<td>Pyrite and chalcopyrite with minor galena in quartz veins and pegmatite within Lander Rock Formation, spatially associated with ca 1567 Ma Southwark Suite.</td>
<td>Scrimgeour (2013)</td>
</tr>
<tr>
<td></td>
<td><strong>Rock Hill</strong> [Cu-Au-(Ag-Pb)]</td>
<td>Pyrite and chalcopyrite with minor galena in quartz veins and pegmatite within Lander Rock Formation, spatially associated with ca 1567 Ma Southwark Suite.</td>
<td>Fruzzetti (1971), Scrimgeour (in press a)</td>
</tr>
<tr>
<td></td>
<td><strong>Clark</strong> [Cu-Au-Ag]</td>
<td>Malachite, azurite, chalcopyrite, pyrite, bornite in quartz veins and pegmatite spatially associated with ca 1567 Ma Southwark Suite granite.</td>
<td>Scrimgeour (in press a), and references therein</td>
</tr>
<tr>
<td></td>
<td><strong>Silver King</strong> [Cu-Ag-Pb-Zn]</td>
<td>Quartz-rich greisen and leached porphyry veins spatially associated with Yalogoarrie Granite which may be part of Southwark Suite.</td>
<td>Warren (1974), Young (1995a)</td>
</tr>
<tr>
<td></td>
<td><strong>Reward</strong> [Cu-Au-Ag]</td>
<td>Malachite, azurite and chalcocite in brecciated shear zone spatially associated with ca 1805 Ma Anmatjira Orthogeeness.</td>
<td>ABM Resources, ASX Announcement, 13/5/2010, Scrimgeour (in press a)</td>
</tr>
<tr>
<td></td>
<td><strong>Harding Springs</strong> [Cu-Au]</td>
<td>Chalcopyrite, djurleite, malachite and Fe-oxides hosted in oblique shear zones and quartz veins cutting oxidised, I-type, ca 1770 Ma Arenara Granodiorite.</td>
<td>Whelan et al (2009a, b, in press)</td>
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<td></td>
<td><strong>Pinnacles copper district</strong> [Cu-(Au-Ag-Bi)]</td>
<td>Chalcopyrite, malachite, chalcocite and bornite in shallowly dipping, quartz-siderite veins concordant with bedding in host marble of Cadney Metamorphics. Veins are interpreted to have formed during ca 450–300 Ma Alice Springs Orogeny.</td>
<td>Warren (1974), Huston et al (2006), Scrimgeour (in press a)</td>
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<td></td>
<td><strong>Shear zone-hosted</strong></td>
<td><strong>Home of Bullion</strong> [Cu-Pb-Zn-Ag-Au]</td>
<td>Four shear zone-hosted, massive sulfide lenses within Bullion Schist. Models for formation include VMS or an epigenetic origin.</td>
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<td></td>
<td><strong>Hydrothermal</strong></td>
<td><strong>Kongs Copper Queen, Copper King</strong> [Cu-Au-(Ag-Pt-Pd)]</td>
<td>Mineralised quartz-carbonate-tourmaline veins associated with chlorite-haematite altered mafic amphibolite.</td>
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### Warumpi Province

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<tr>
<td>Mount Larrie (?) [Cu]</td>
<td>Malachite stained garnet-feldspar-quartz rock, thought to be hydrothermal or magmatic in origin, hosted in Alkpi Metamorphics.</td>
<td>Clark (1975), Scrimgeour et al (2005a), Scrimgeour (in press b)</td>
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### Irindina Province

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**Table 1.** Summary of Cu ± Au occurrences in Aileron, Warumpi and Irindina provinces.
comprises three fault-bounded domains; the Haasts Bluff, Yaya and Kintore domains (Close et al. 2003, Scrimgeour et al. 2005b, Scrimgeour in press b).

The amphibolite-facies Haasts Bluff Domain, the oldest of the three, is dominantly an igneous terrane. Igneous rocks have been interpreted to reflect magmatism in a continental arc outboard of the North Australian Craton (Close et al. 2005). The domain is dominated by amphibolite-facies intrusive, volcanic and less metamorphic, rocks, emplaced or deposited during the interval 1690–1660 Ma; this is unformably overlain by a younger cover successions interpreted to have been deposited after the 1640–1630 Ma Leibig Orogeny (Scrimgeour et al. 2005b, Scrimgeour in press b).

In contrast, the upper-amphibolite- to granulite-facies Yaya Domain is characterised by a slightly younger supracrustal succession, interpreted to have been deposited during the interval 1660–1640 Ma and intruded by voluminous ca 1640–1630 Ma felsic and lesser mafic suites. Metamorphic grade ranges from upper-amphibolite facies in the west to granulite-facies in the east (Scrimgeour et al. 2005b, Scrimgeour in press b). The grenschist-facies Kintore Domain forms the westernmost part of the Warumpi Province and extends into Western Australia. The Kintore Domain comprises basement of 1690–1685 Ma granites, overlain by a younger supracrustal succession comprising quartzite, phyllite and felsic, intermediate and mafic volcanic rocks. Unlike the Haasts Bluff and Yaya domains, significant areas of the Kintore Domain show no evidence of pervasive fabric development (Scrimgeour in press b).

Although the Warumpi Province is the least explored province in the Arunta Region, previous NTGS studies have highlighted a significant potential for base metals, including IOCG-style mineralisation, as well as mafic-hosted Ni-Cu (Close et al. 2004, Scrimgeour in press b). The Mount Larrie Cu prospect (Table 1) is hosted in malachite-stained garnet-feldspar-quartz rock, thought to be hydrothermal or magmatic in origin, in the Alkipi Metamorphics (Scrimgeour in press b). Mineralisation comprising malachite, azurite and minor chalcopyrite (locally magnetite and pyrite) is patchy and ranges up to 5.9% Cu (Clark 1975, Scrimgeour in press b). The Haasts Bluff Cu ± Au prospect (Table 1, Barralough 1975, Scrimgeour et al. 2005a), broadly classified as IOCG-style (Frater in prep), is hosted in mafic amphibolite, calc-silicate rock and marble within quartz-feldspar-mica schist of the Ikuntji Metamorphics (Scrimgeour in press b). Copper grades are up to 27.7% and Au up to 0.8 g/t (Frater in prep).

Irindina Province

The Irindina Province (Figure 1a, Scrimgeour 2003) is a thick succession of Neoproterozoic to Cambrian, granulite- to amphibolite-facies metasedimentary rocks (Harts Range Metamorphic Complex) and subordinate meta-igneous rocks. It includes correlates of the Centralian Superbasin succession (Maidment 2005). The province has a tectonic contact with the Aileron Province and is unformably overlain by the northwestern extent of the Eromanga Basin (Scrimgeour in press c). The sedimentary precursors to the Harts Range Metamorphic Complex have been interpreted to have been deposited in an east–to-southeast-trending Cambrian, fault-bounded extensional basin. High-grade metamorphism of the succession during the ca 480–460 Ma Larapinta Event (Mawby et al. 1999, Hand et al. 1999, Maidment 2005) is thought to have occurred as a consequence of deposition at the base of an extremely deep sub-basin (Buick et al. 2005). The province was then exhumed and juxtaposed against the Aileron Province during the 450–300 Ma Alice Springs Orogeny (Mawby et al. 1999, Hand et al. 1999, Maidment 2005).

The Harts Range Metamorphic Complex comprises a succession of pelitic and psammopelite metasedimentary rocks, metabasite (and associated first-cycle, juvenile metasedimentary rocks) and calc-silicate rock, with subordinate marble, quartzite and felsic gneiss (eg Scrimgeour in press c, Whelan et al. in prep b). Five main periods of magmatism have been identified in the province: (1) ca 530 Ma voluminous rift-related tholeiitic intrusions with subordinate volcanic rocks of the Riddock Amphibolite; (2) ca 520 Ma dominantly felsic plutons of the Indiana Igneous Complex; (3) the ca 507 Ma Coggans Gabbro, geochemically and temporally similar to the Kalkarindji Suite; (4) the ca 409 Ma Lloyd Gabbronorite; and (5) ca 350 Ma peraluminous granite and granitic pegmatite intrusions (Whelan et al. 2010, Whelan et al. in prep b).

Like the Warumpi Province, the Irindina Province has seen little exploration activity, despite its potential across a range of commodities, including mafic-hosted Ni-Cu-PGE, copper and polymetallic base metals. In 2008, while following-up reports of secondary copper mineralisation identified during NTGS mapping in the eastern Arunta Region, Mithril Resources Ltd (Mithril) discovered the Blackadder and Baldrick Ni-Cu-PGE prospects. These prospects comprise orthomagmatic mineralisation hosted in the Devonian Lloyd Gabbronorite. In 2009, during exploration for more Ni-Cu-bearing mafic intrusions, Mithril discovered the Basil Cu-Co prospect, hosted in the voluminous Riddock Amphibolite, close to the structural contact with the Aileron Province. Mineralisation extends for 10 km along strike and is characterised by massive (20–50%) and stringer sulfides, comprising pyrrhotite, pyrite and chalcopyrite. Copper-bearing gossan forms the surface expression of additional parallel zones at the nearby Poly and Manuel prospects (McKinnon Matthews 2010). Sharrad (2012) has tentatively assigned the mineralisation at Basil and associated Cu-Co occurrences to a metamorphosed VMS-style system. The lack of recognisable hydrothermal alteration is consistent with the destruction of the alteration zone during an overprinting metamorphic event, or detachment of the alteration zone from the ore during synmetamorphic deformation (Sharrad 2012). Moreover, the presence of sulfide inclusions in garnet and amphibole of the Riddock Amphibolite suggest that mineralisation occurred prior to, or syn-metamorphism. Crystallisation of ore minerals is interpreted to have occurred at pressures of 10 kbar (Sharrad 2012). This suggests that mineralisation
is likely to have occurred prior to the high-grade Larapinta Event, which reach pressures of up to 10–12 kbar (Miller et al. 1997, Mawby et al. 1999, Buick et al. 2001, Scrimgeour and Raith 2001). A number of other Cu occurrences are hosted in the Riddock Amphibolite to the northwest, including Selins (Cu-Zn) and Virginia (Cu) in ALICE SPRINGS®. These are both associated with garnet-quartz-hornblende rocks, along with anthophyllite rock and garnet quartzite. Garnet-quartz-hornblende assemblages are also evident in drill core from the Basil prospect (Sharrad 2012) and may indicate that these occurrences share a common petrogenesis.

**Intrusion-related Cu-Au potential of the Aileron Province**

**Mineralisation styles, alteration footprints and structural controls of Cu ± Au prospects in the Aileron Province**

A number of mineralisation styles for Cu (±Au, ±base metals) is apparent for each of the provinces in the Arunta Region, as discussed above. Recent investigations by NTGS has highlighted the potential for IOCG-style mineralisation in the Aileron Province and the remainder of this abstract will focus on the potential of the Aileron Province for such systems, including regional-scale alteration styles and structural controls, and potential sources for metals.

The Aileron Province has a relatively limited mining history and is underexplored in comparison to other Proterozoic regions in the Northern Territory, such as the Pine Creek Orogen and the Tennant and Tanami regions. Recent work undertaken by NTGS in the eastern (ILLOGWA CREEK and HUCKITTA) and central Aileron Province (NAPPERBY) has identified regional-scale alteration systems similar to those that are associated with intrusion-related IOCG-style mineralisation (Whelan et al. 2011, Beyer et al. 2012, Whelan et al. 2012).

In NAPPERBY, evidence of widespread hydrothermal fluid flow and associated alteration during the ca 1590–1560 Ma Chewings Orogeny has been identified and is interpreted to share characteristics with alteration associated with IOCG systems (Beyer et al. 2012a, b). This includes strongly oxidised, greisenised granite and extensive areas overprinted by haematite-silica metasomatism and potassic alteration assemblages overprinting what has been interpreted to be Heavitree Quartzite. The youngest zircon ages (ca 1119 Ma; Kositcin et al. in prep) obtained from this sample were acquired from very low-U rims, which may represent either new metamorphic zircon growth or hydrothermal zircon growth, during remobilisation of Cu-haematite fluids from the nearby Atneequa Suite.

SHRIMP U-Pb zircon geochronology of a sample of haematite-altered, deformed (locally mylonitic) quartzite, suggests that at least some of the mineralisation may have been remobilised along these crustal-scale structures, with haematite-Cu assemblages overprinting what has been interpreted to be Heavitree Quartzite. The youngest zircon ages (ca 1119 Ma; Kositcin et al. in prep) obtained from this sample were acquired from very low-U rims, which may represent either new metamorphic zircon growth or hydrothermal zircon growth, during remobilisation of Cu-haematite fluids from the nearby Atneequa Suite. Furthermore, SHRIMP U-Pb and O analyses of zircon rims from a sample of the Albarta Metamorphics in northwestern LIMBLA, yielded 207Pb/206Pb ages in the order of ca 1105 Ma. Oxygen isotope studies of these zircon rims yielded very low δ18O values of ca 0.80‰, much lower than those of the zircon cores, which were in the range 6.04–8.80‰. On this basis, we interpret a hydrothermal origin (eg Wei et al. 2002 and references therein) for new zircon growth at ca 1105 Ma. The ages reported here are similar to, or slightly postdate Sm-Nd garnet and LA-ICPMS U-Pb monazite ages obtained from the eastern Warumpi Province, interpreted to represent reworking of the basement during what is

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*N Names of 1:250 000 and 1:100 000 mapsheets are in large and small capital letters respectively, eg ALICE SPRINGS, LIMBLA.

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At Rock Hill, mineralisation comprises mainly malachite, subordinate azurite and chrysocolla, hosted in quartz veins and pegmatite, and it is interpreted that metals may have been derived from the nearby K-rich Wakurlpa Granite of the ca 1567 Ma Southwark Suite (Young et al. 1995a, b, Budd 1997). Although characterised by higher-grade mineralisation, like Rock Hill, the Mount Hardy deposits comprise chalcopyrite and pyrite with subordinate galena, hosted in quartz veins and pegmatite. Budd (1997) suggested that the likely source of Cu is the nearby Yarunganyi Granite, which also belongs to the Southwark Suite and this highlights the potential of this suite for Cu-Au mineralisation.

To the southeast, in ILLOGWA CREEK, large areas of ca 1750–1740 Ma Atneequa Suite intrusions have been intensely altered by fluorite-haematite-silica-bearing fluids, associated with hydrothermal brecciation of the granite (Figure 2a). The alteration assemblage is characterised by fluorite-silica-haematite-magnetite and potassic assemblages and is described in detail by Lyons et al. (2013). Alteration is particularly focused around (but not restricted to) regional-scale west- to northwest-trending structures (Whelan et al. 2011, 2012, McKinnon Matthews 2011, Lyons et al. 2013). A number of these structures are responsible for thrusting Palaeoprotorezoic basement rocks against the basal Neoproterozoic succession of the unconformably overlying Amadeus Basin. Exposed along, or within the vicinity of these structures is sporadically outcropping Cu ± Au mineralisation, forming the newly identified Illogwa IOCG belt (Lyons et al. 2013). Ore minerals include chalcopyrite, pyrrhotite and pyrite, with malachite common at the surface (Figure 2b). Lyons et al. (2013) described drilling results for prospects in the Illogwa IOCG belt and noted the proximity of the prospects to regional-scale structures. It should also be noted that these prospects occur in an area interpreted to have been the Palaeoprotorezoic southern margin of the North Australian Craton.

New SHRIMP U-Pb zircon geochronology of a sample of haematite-altered, deformed (locally mylonitic) quartzite, suggests that at least some of the mineralisation may have been remobilised along these crustal-scale structures, with haematite-Cu assemblages overprinting what has been interpreted to be Heavitree Quartzite. The youngest zircon ages (ca 1119 Ma; Kositcin et al. in prep) obtained from this sample were acquired from very low-U rims, which may represent either new metamorphic zircon growth or hydrothermal zircon growth, during remobilisation of Cu-haematite fluids from the nearby Atneequa Suite. Furthermore, SHRIMP U-Pb and O analyses of zircon rims from a sample of the Albarta Metamorphics in northwestern LIMBLA, yielded 207Pb/206Pb ages in the order of ca 1105 Ma. Oxygen isotope studies of these zircon rims yielded very low δ18O values of ca 0.80‰, much lower than those of the zircon cores, which were in the range 6.04–8.80‰. On this basis, we interpret a hydrothermal origin (eg Wei et al. 2002 and references therein) for new zircon growth at ca 1105 Ma.
becoming a regionally recognised tectonothermal event in the southern Arunta Region (eg Morrissey et al 2011). Although the new age data reported here is of similar timing to that of tectonic reworking in the Warumpi Province, based on the hydrothermal O isotope signature of ca 1105 Ma zircon rims, it is suggested that these ages may represent the timing of a fluid flow event, which was responsible for remobilising Cu-Au mineralisation from the basement and depositing it in regional-scale structures in the Illogwa IOCG belt.

A similar style of alteration and brecciation is visible in drill core from the Perenti Cu-Au prospect, located approximately 150 km north-northwest of the Illogwa IOCG belt in HUCKITTA. The Perenti prospect is located within a wide belt of northwest-trending, regional-scale structures that are parallel to, or form branches of the Delny-Mount Sainthill Shear Zone. At Perenti, pyrite, chalcopyrite, haematite-bearing quartz veins (Figure 2c) cut strongly foliated to mylonitic biotite granite of unknown age. Below the mineralisation, the granite is characterised by intense red-rock alteration and appears to be relatively undeformed and porphyritic. Moreover, new HyLogger results for drillhole DDNT12-2 indicate that the white mica and feldspar mineralogy of the granite above and below the mineralised zone are different. NTGS is currently undertaking geochemical and geochronological studies to determine the nature and timing of these two potentially different granites. Immediately to either side of the mineralised quartz veins, the granite(s) show intense haematite-chlorite-fluorite alteration and brecciation. Red-rock alteration appears to be at its most intense below the mineralised veins.

### Potential sources of metals and F-rich magmas

A number of previous NTGS studies have highlighted a broad spatial correlation between ca 1780–1760 Ma intrusions emplaced syn- to post-Yambah Event (eg Close et al 2007, Whelan et al 2009, Beyer et al 2013) and Cu-Au occurrences in the Arunta Region. However, it appears that there is a significant association between not only Yambah-aged intrusions, but also with strongly oxidised, high-K, high-F, intrusions of the ca 1750 Ma Atneequa Suite (and a number of unnamed intrusions to the north in HUCKITTA and ILLOGWA CREEK) in the eastern Arunta Region (Whelan et al 2012). In the central Arunta Region, there appears to be a significant association between high-K ca 1567 Ma intrusions of the Southwark Suite, Yambah-aged intrusions of the Carrington Suite and Cu-Au occurrences including Mount Hardy and Rock Hill in MOUNT DOREEN.

The Yambah Event is the dominant magmatic event across the southern half of the Aileron Province and appears to represent a southward migration of the loci of magmatism following the ca 1810–1790 Ma Stafford Event (Scrimgeour in press a). Suites of Yambah age are dominantly I-type and include mafic and felsic metaluminous intrusions, the mafic to intermediate lithologies of which commonly contain Fe- and Cu-bearing sulfides and are elevated in metals (eg Whelan et al 2009a, Beyer et al 2012). Fluids associated with the intrusion of high-K, high-F magmas at ca 1750 Ma in the eastern Arunta Region and again at ca 1567 Ma in the central and northern Arunta Region may have been responsible for liberating and transporting metals from the more metaluminous, juvenile intrusions (with mantle-derived
mafic end-members) emplaced during the Yambah Event. Deposition of metals, at least in the eastern Arunta Region appears to have occurred in the vicinity of, or along major crustal scale-structures, which may have acted as conduits for fluid flow and metal deposition on a number of occasions from the Palaeoproterozoic through to the Mesoproterozoic.

Summary

The Arunta Region is prospective for a wide range of copper mineralisation styles and is particularly prospective for intrusion-related systems, such as IOCG in the Aileron and Warumpi provinces. The identification of regional- and local-scale alteration systems at various locations in the Arunta Region, particularly in the eastern Aileron Province, combined with new discoveries of outcropping Cu ± Au mineralisation, indicate the potential for this underexplored Palaeoproterozoic province. Voluminous felsic and juvenile mafic magmas, intruded during the ca 1780–1760 Ma Yambah Event on the southern margin of the North Australian Craton, may have provided a reservoir of metals. Successive emplacements of high-K, high-F dominantly peraluminous granites at ca 1750 and 1567 Ma may have liberated metals from the mafic intrusions and deposited them along regional and local-scale west to northwest-trending structures. In the eastern Arunta Region, regional scale fluid flow ca 1105 Ma may have facilitated further remobilisation of metals from the basement.

References


In 2010, during the course of regional mapping on a Mithril Resources Pty Ltd (Mithril) exploration lease, located about 160 km east of Alice Springs, NTGS found haematite and fluorite veins in brecciated granite, indicating the possible presence of IOCG mineralisation (Whelan et al 2012). Following this, Mithril conducted a regional soil geochemical survey, which led to the discovery of a strike ridge of quartz-haematite-carbonate veins, containing copper carbonates, boxworks, pyrite, and chalcopyrite, located about four kilometres north of the NTGS site. The veins are hosted in brecciated granite with extensive potassic, hydrolytic, and haematitic alteration (including red rock). Subsequent fieldwork established the existence of potassic, hydrolytic, and haematitic alteration (including copper carbonates, boxworks, pyrite, and chalcopyrite, with the interval averaging 0.18% Cu (maximum 0.67% Cu; Figure 1). Low grade Au has also been found in percussion drill chips (0.364 ppm). Detailed mineralogical studies of the mineralisation and alteration are planned.

The Illogwa IOCG Belt trends west-northwest and is situated about 5 km south of Ilogwa Creek, to which it is roughly parallel. The belt, as currently identified, extends from the edge of the Simpson Desert in the east, to an area about 6 km south of Albarta Dam in the west. It has not been mapped farther west, as this is outside Mithril’s lease. Nearly half of the belt is exposed. The vein sets generally dip about 60° to slightly east of north and are up to 200 m wide. Alteration haloes can be 500–600 m from the midline of the vein sets. In places, the host rocks are mylonite related to mantle-tapping structures of the Ataun Inlier (Huston et al 2011), suggesting that the mineral system is correspondingly large.

Although the field evidence was consistent with the presence of an IOCG mineral system, confirmation required the examination of unweathered samples. A program of diamond drilling (co-funded through Round 5 of the NT Government’s Geophysics and Drilling Collaboration program) showed that the mineralisation is part of an IOCG mineral system. Five diamond holes were drilled into targets selected along the length of the belt. Core from each hole contained hydrolytic and potassic alteration and on magmatism in the eastern Arunta Region, central Australia: Implications for source regions and Palaeoproterozoic tectonism: in Proceedings from the 34th International Geological Congress: Brisbane, 2012, Abstracts #3162.


of mineralisation, veining, or alteration has been found in basal units of the overlying Amadeus Basin, it is likely that the system is not younger than 850 Ma.

The Illogwa IOCG Belt is situated in a part of the eastern Arunta Region that was practically unexplored until 2010. Its discovery shows that the potential for greenfields mineralisation is not confined to regions under cover (this is Mithril’s second significant find in exposed basement of the eastern Arunta Region; see McKinnon-Matthews 2010). Although exploration of the Illogwa IOCG Belt is still in its early stages, significant conductivity and chargeability anomalies have already been identified and will be drill-tested this year. As IOCG mineralisation commonly occurs in provinces hundreds of kilometres long (eg Olympic Copper Gold Province, Carajás Mineral Province), there is little reason to doubt that the Illogwa IOCG Belt is part of a much larger entity.

References


A brief review of Palaeoproterozoic (ca 1860–1700 Ma) magmatism in the Tennant Region and its possible palaeotectonic implications

Nigel Donnellan

Introduction

The Northern Territory Geological Survey is undertaking an interpretation of geochemical data for ca 1840–1800 Ma mafic and intermediate rocks from the Davenport and southern Warramunga provinces of the Tennant Region and is assessing the implications of these data for their petrogenesis. This work is using new data resulting from systematic sampling of selected rock units, together with previously available data, and will be reported separately. The brief outline of Palaeoproterozoic magmatism in the Tennant Region presented here aims to provide a wider contextual background to this study.

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Tennant Region magmatism is of interest for a number of reasons: (1) there are possible palaeotectonic implications for the Tennant Region; (2) magmatic rocks have a temporal/spatial association, in particular with the polymetallic Tennant Creek-style iron-oxide copper-gold mineralisation, but also with other styles of mineralisation in the region; (3) stratiform magmatic rocks of the region can be traced in semi-regional airborne magnetic data undercover to the south, east and west of the outcropping Tennant Region and may contribute to understanding the broader inter-regional geological context in the time interval ca 1840–1800 Ma.

The summary of Tennant Region magmatism presented here broadly follows an approach that was recommended by Cas and Wright (1987) for the palaeotectonic interpretation of volcanic terranes. It includes the following considerations: (1) the mapped distribution of magmatic rock units in a number of discrete age brackets throughout the region; (2) the types and series of magmatic rocks in each magmatic episode; (3) the types and facies of sedimentary rock units that were deposited contemporaneously with the magmatic units and in the time intervals between magmatic events; and (4) a comparison with similar more recent terranes where the tectonic environment is known.

Geology of the Tennant Region

An outline of the geology of the Tennant Region has been presented elsewhere (Donnellan 2005), so only a few relevant points are given here. Palaeoproterozoic rocks of the Tennant Region in central Australia are exposed over an area of about 45 000 km². The region is divided from north to south into the Tomkinson, Warramunga and Davenport provinces, and the stratigraphic succession into the Tomkinson Creek, Ooradidgee and Hatches Creek groups (Figure 1). The Tomkinson Creek and Hatches Creek groups have been correlated lithostratigraphically. In detail, there are some differences in their local successions and their interpreted palaeoenvironments of deposition, and the Warramunga Province may have partially separated two basins or sub-basins to the north and south. The Warramunga and Junalki formations and the Woodenjerrie beds at the base of the Warramunga Province succession have not been assigned to a formal group. These rocks include volcanic rocks and/or volcanoclastic material, and are locally unconformably overlain by the Ooradidgee Group. This group comprises bimodal volcanic and sedimentary rocks with a substantial component of fluvialite deposits (Sweet in Blake et al 1987), but shallow water and offshore marine facies probably increase to the north. Intrusive rocks (mainly granite, granodiorite and porphyry with minor outcropping dolerite and gabbro) are interpreted to be comagmatic with older, ca 1850–1840 Ma Ooradidgee Group volcanic rocks and together, these comprise the Tennant Creek Supersuite of Wyborn et al (1998) that is in part syntectonic with respect to the Tennant Event.

Generally stratiform dolerite (and gabbro) intrudes the Ooradidgee Group, mainly in the Warramunga Province, and the lower Tomkinson Creek Group in the Tomkinson Province. The dolerite is interpreted to be associated with extension at ca 1820–1810 Ma (in Murchison Event). It is locally penecontemporaneous with shallow intrusive granophyres that, together with the younger bimodal volcanic rocks of the Ooradidgee Group and immediately overlying Wauchope Subgroup, were assigned to the Treasure Suite by Wyborn et al (1998). Prior to this widespread extension, volcanism appears to be located around discrete centres and to have resulted in the complex lateral facies variations associated with the Ooradidgee Group. Subsequent stratigraphic successions, the Hatches Creek and Tomkinson Creek groups, are more layer-cake. In the Davenport Province, predominantly volcanic or sandstone intervals succeed one another in the Wauchope Subgroup while volcanic rocks are minor in the overlying Hanlon Subgroup. The Tomkinson Creek Group generally lacks volcanic rocks and is also more carbonate-rich than the Hatches Creek Group.

![Figure 1. Simplified stratigraphy of Tennant Region.](image)
Figure 2. Interpretative rock-relationship diagram for Ooradidgee Group in Warramunga and Davenport provinces (after Donnellan in press, figure 9.4). This diagram is consistent with relationships between individual stratigraphic units that were described from original mapping (eg Blake et al 1987, Donnellan et al 1999). Approximate thicknesses of individual units are shown to scale on vertical axis of diagram. Time is also shown on vertical axis; scale for time is variable and various time horizons (ca 1860 Ma, 1850 Ma, 1840 Ma, 1820 Ma and 1810 Ma) are indicated. Ages are from Claoué-Long et al (2008), Smith (2001) and Compston (1995).
The Kudinga Basalt, the uppermost unit of the Wauchope Subgroup, is widespread in the Davenport Province and is correlated with the Whittington Range Volcanic Member in the Tomkinson Creek Group (Blake 1984). The latter is poorly exposed, but is interpreted from semi-regional airborne magnetic data to be widespread in the Tomkinson Province. The youngest mapped volcanic rocks outcrop in the Alinjabon Sandstone, >3 km below the top (as currently preserved) of the Hatches Creek Group. Devils Suite magmatism ca 1710 Ma and associated lamprophyres may have been contemporaneous with, or postdated Davenport Event folding.

**Magmatic episodes in the Tennant Region**

The relationships between individual stratigraphic units of the ca 1850–1805 Ma Ooradidgee Group are summarised in Figure 2; overlying units generally have a layer-cake geometry. In conjunction with currently available geochronological data, these mapped relationships suggest that there were five main magmatic episodes in the Tennant Region; these occurred at ca 1860, 1850, 1840, 1820–1805 and 1720–1700 Ma (Figure 3). Previously, Wyborn et al. (1998) had divided the magmatic rocks of the Tennant Region into (approximately) three suites: (1) the ca 1850–1840 Ma Tennant Creek Supersuite; (2) the ca 1820–1805 Ma Treasure Suite; and (3) the ca 1720–1700 Ma Devils Suite.

Hoatson et al. (2007, 2008) recognised representatives of three of their Australian Proterozoic mafic-ultramafic magmatic events in the Tennant Region: the ca 1850 Ma Mumbilla Event (of the Australia-wide Sally Malay Event), the ca 1840 Ma Edmirrigeec and ca 1810 Ma Mount Hay events. The Mumbilla Event is represented by rare outcropping dolerite dykes in Tennant Creek Supersuite granites. Similar dykes have been intersected in drill-core and have been interpreted from geophysical data. The Edmirrigeec Event is represented by the eponymous volcanic rocks, together with minor gabbro and dioritic intrusive rocks. The Mount Hay Event includes mafic extrusive rocks of the Treasure Volcanics and penecontemporaneous unnamed dolerite and gabbro that intrude the Ooradidgee Group in the Kurinelli, Hatches and Last Hope areas and the Hayward Creek Formation in the Tomkinson Province. Unnamed 1711 ± 2 Ma (Claoué-Long et al. 2008) lamprophyre dykes are penecontemporaneous with the Devils Suite granites.

Details of the distribution of igneous rocks are given as a series of time-slice maps in the presentation associated with this abstract.

**Magmatic rocks in the Tennant Region**

**Volcanic rocks**

Tennant Region volcanic rocks include basic and intermediate lavas, and felsic pyroclastic rocks and lavas. A variety of rock compositions have been recognised in the field and from petrographic studies, but alteration is widespread and the rocks have also undergone low-grade metamorphism. For this reason, the samples plotted on the total alkali oxide vs silica (TAS) classification of Le Maitre (1989) in Figure 4 are mainly those where, on geochemical (see, for example, Donnellan et al. 1995, 2001) and/or petrographic grounds, their chemical composition is apparently least impacted by alteration and metamorphism was broadly isochemical. However, low-grade metamorphism involves hydration and some samples shown in this plot have loss on ignition >2.5 wt%, including basalts from the Treasure Volcanics. Some samples from, for example, the Skinner Pound volcanic centre of the Edmirrigeec Volcanics are sheared and markedly epidotised and cannot be included. So, without seeking to rigorously classify the Tennant Region volcanic rocks, the TAS diagram suggests that they: (1) are bimodal; (2) include low-silica intermediate rocks; and (3) belong to both the subalkaline and transitional (tholeiitic/weakly alkaline) rock series; the latter includes basalt and possible hawaiite and mugearite. Samples of transitional basalt have low (<10 wt%) normative hypersthene and no normative

**Figure 3.** Magmatic episodes in Tennant Region. Tennant Creek Supersuite, Treasure and Devils suites were named by Wyborn et al. (1998), and mafic-ultramafic magmatic events are from Hoatson et al. (2007).
quartz. Minor mugearite has previously been recognised in the Edmirringee Volcanics on petrographic evidence (Stewart and Blake 1986). However, some samples with preserved igneous textures, including polysynthetically twinned plagioclase, are albited and their plagioclase shows deformation lamellae.

Zr vs Ti relationships (Figure 5) corroborate bimodality between mafic/low-SiO$_2$ intermediate rocks and felsic rocks. The diagram further indicates that the felsic volcanic rocks are not likely to be fractionation products of the mafic ones. The possibility of transitional rock compositions requires independent corroboration using immobile incompatible elements, but may be complicated by the rock’s continental signature. For example, Nb/Y ratios are low by comparison with typical alkaline rocks, but the crustally contaminated transitional tholeiitic/alkalic Mull Plateau Group volcanic rock series also have subalkaline Nb/Y ratios (Kerr et al 1999). Samples of the Kudinga Basalt have gently uniformly sloping chondrite-normalised REE patterns with slight negative Eu-anomalies (Stewart and Blake 1986). However, some samples with preserved igneous textures, including polysynthetically twinned plagioclase, are albited and their plagioclase shows deformation lamellae.

Shallow intrusive rocks

These include mainly dolerite (gabbro), rhyolitic to dacitic granophyre, and felsic (dacitic and rhyolitic) porphyry, but also include diorite, monzodiorite and lamprophyre. Widespread emplacement of basic sills in the southern Warramunga and Tomkinson provinces at ca 1820–1810 Ma is interpreted to have been associated with extension during the Murchison Event. The REE element geochemistry of the unnamed dolerite and former ‘Pedlar Gabbro’ is compared in Figure 6. The gabbro is comparable with the gently uniformly slope of one of the two apparently discrete types of chondrite-normalised pattern in the mafic Treasure Volcanics. The unnamed dolerite has similar, but slightly more LREE-enriched patterns, while the Kudinga Basalt has more steeply uniformly sloping patterns, and consistently shows plagioclase fractionation. The unnamed dolerite, gabbro and Treasure Volcanics that have gently uniformly sloping REE-patterns may be related by assimilation and fractional crystallisation (AFC; Donnellan in prep). The predominant group of Treasure Volcanics mafic rocks, in contrast, have boninite-like REE patterns (Figure 6).

Intrusive felsic porphyry is mainly associated, and consanguineous with the ca 1850 Ma Tennant Creek Supersuite granites. Some porphyries have very high-K$_2$O and are metasomatised, and others are sheared and strongly altered, eg the White Devil porphyry (Huston and Cozens 1994). The intrusive porphyries have a wide variety of, sometimes apparently contradictory field relationships. These include locally cross-cutting the regional foliation in the Warramunga Formation, and peperitic breccia textures that McPhie (1993) interpreted to have resulted from intrusion of porphyry into wet, unconsolidated sediments at substantial water-depths. A possibly analogous setting was described by Marques et al (2010), who described tight to very tight/isoclinal folding, with an associated penetrative axial planar cleavage, in very low-grade metaturbidites in a Variscan foreland fold-thrust belt in the South Portuguese Terrane. This deformation was inferred to have been penecontemporaneous with dehydration and compaction of the sediments (ie pre- to syn-lithification), and may only be locally developed or preserved due to overprinting in the then-lithified rocks at slightly higher metamorphic grade. A
similar situation may have prevailed in the Tennant Region, involving deformation in the Warramunga Formation penecontemporaneous with porphyry sill emplacement.

Jaques et al (1985) classified the lamprophyres as mainly minettes, but they may include rare vogesites (Crohn and Oldershaw 1965). Duggan and Jaques (1996) divided these ultrapotassic (shoshonitic affinity) minettes into two spatially discrete groups, mainly on the basis of their Zr/Nb ratios, that were derived from a heterogeneous, crustally contaminated, subcontinental lithospheric mantle source.

**Granite**

Outcropping granitic rocks in the Tennant Region are mainly included in the ca 1850 Ma Tennant Creek Supersuite and ca 1710 Ma Devils Suite of Wyborn et al (1998), although granophyre in the vicinity of the Hatches mineral field belongs to the ca 1810 Ma Treasure Suite. Tennant Creek Supersuite granites include biotite- to biotite-bearing rapakivi-granite, biotite- to biotite-bearing K-feldspar megacrystic granodiorite, and minor tonalite (Donnellan et al 1995). Details of alteration in the Tennant Creek Supersuite were reported by Donnellan et al (1995, 2001), and the rocks are classified as high-K calc-alkaline (Figure 7). The granites are peraluminous to weakly metaluminous. Wyborn (1988) noted that granodioritic rocks were widespread at this time in northern Australia and that granitic rocks of this age may in general be more alkali-calcic than calc-alkaline, and are I-type.

Devils Suite granites are of the fractionated I-(granodiorite) type, and are also fluorite-bearing (Wyborn et al 1998) and locally associated with tungsten mineralisation. These granites form discrete, sub-circular non-magnetic bodies with the relatively low gravity response that is typical of post-tectonic granites, although some, eg the Kaidwalla Granite, are foliated. Whereas post-tectonic, I-type granite and potassic lamprophyre are closely associated at Mount Bundey in the Pine Creek Orogen (see Müller and Groves 1995), lamprophyre and penecontemporaneous granite are generally spatially separated in the Tennant Region.

**Palaeotectonic inferences from Tennant Region magmatism**

Bimodality is often associated with rift settings, although the Daly Gap (ie absence or paucity of intermediate rock compositions) was first recognised in volcanic sequences in ocean islands and is therefore not necessarily diagnostic. McBirney (2007) noted that bimodality is well developed in calc-alkaline provinces in block faulted areas of the continents including continental margins. An association between continental flood basalts and rhyolite has been described from a number of large igneous provinces (LIPs). For example, in the Paraná-Entendeka Province in southern Central America and Namibia, Peate (1997) has recognised both high- and low-Ti late-stage rhyolites. However, the relative proportion of felsic to mafic volcanic rocks and the fact that felsic volcanic rocks generally apparently predate the mafic varieties in each bimodal cycle in the Tennant Region is perhaps unusual. Cas and Wright (1987) noted that volcanism in broad intracontinental rifts includes intermediate rock types and a wide spectrum of rock compositions.
series. In contrast, narrow rift zones are characterised by markedly alkaline rocks, with compositions ranging from transitional basalt to nephelinite, olivine-poor nephelinite and carbonatite (Braile et al 1995, Le Bas 1987), and a wide, but localised diversity of rock types similarly characterises the early stages of rifting (Einsele 1992). The Rhone depression and Rhine graben are examples of narrow contemporary rift systems with strongly alkaline basaltic rocks (Prodehl et al 1995), whereas the Rio Grande rift is an example where the basaltic rocks are predominantly subalkaline with subordinate transitional basalts (Baldridge et al 1995).

A two-stage model for the development of ca 1880–1840 Ma felsic volcano-plutonic magmatism in northern Australia was proposed by Wyborn (1988). Wyborn favoured derivation of these felsic rocks, which include the ca 1850 Ma magmatic rocks of the Tennant Region, by infracrustal melting and differentiation of the more fractionated component of previously underplated, enriched mantle-derived melts. Melting may have been a result of mantle upwelling, or plume activity associated with extension, but granite emplacement and comagmatic volcanism in the Tennant Region is at least in part contemporaneous with deformation. Contemporaneous mafic magmatism in the Tennant Region is locally evident in intrusive dolerites. One process by which rapakivi textures can form is the mixing of mafic with felsic magma. So, the rapakivi textures in the Tennant Creek Granite and associated porphyry may provide further evidence of penecontemporaneous mafic magmatism.

A rift-sag model was proposed as the tectonic setting for the Ooradidgee/Hatches Creek groups by Blake and Page (1988). Turbiditic and probable marginal marine rocks of the Lander Rock Formation are widespread in the immediately adjacent Aileron Province in MOUNT PEAKE (Donnellan and Johnson 2003, Donnellan et al 2008) and are correlated with the Ooradidgee Group in the Tennant Region. The presence of stratiform mafic sills and/or volcanic rocks within the Lander Rock Formation succession is demonstrated by airborne magnetic data and sparse outcrop and suggests extension penecontemporaneous with sedimentation. In this context, a wide, enclastic failed-rift and/or extending continental crust (‘possible passive margin’) in the Tennant and adjacent Arunta regions is likely. Staffort Event (ca 1800 Ma) rapakivi- and rapakivi-association (ie rapakivi, K-feldspar megacrystic and more equigranular) granites in MOUNT PEAKE (Donnellan 2008) and NAPPERBY (Stewart et al 1980) are also consistent with an extensional environment by analogy with Proterozoic anorogenic granites in North America (Anderson and Morrison 1992). The Warramunga Province is the locus of the ca1850–1840 Ma Tennant Creek Supersuite and early deformation. Warramunga Formation provenance is consistent with that of passive margin turbidites, and the Warramunga Formation (and its local correlative) may have been deposited in an aurologen, while similarly aged rocks may extend over a much wider area (Korsch et al 2011). It is hoped that work in progress (Donnellan and carbonatite (Braile et al 1995, Le Bas 1987), and a wide, but localised diversity of rock types similarly characterises the early stages of rifting (Einsele 1992). The Rhone depression and Rhine graben are examples of narrow contemporary rift systems with strongly alkaline basaltic rocks (Prodehl et al 1995), whereas the Rio Grande rift is an example where the basaltic rocks are predominantly subalkaline with subordinate transitional basalts (Baldridge et al 1995).

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2 Names of 1:250 000 mapsheets are shown in large capital letters, eg MOUNT PEAKE.

in prep) on the mafic rocks from the Tennant Region will further test this model, providing an insight into the nature of their penecontemporaneous mantle source(s) and any asthenospheric mantle upwelling or possible plume activity.

Acknowledgements

I would particularly like to thank my former colleagues at NTGS, Kelvin Hussey and Dr Bob Morrison, with whom I mapped in TENNANT CREEK. Dr David Blake (GA, formerly BMR) led the mapping program in the Davenport Province and, what is now the southern Warramunga Province. This work resulted in many new insights that are relevant to the geology of the wider Tennant Region, and also resulted in the collection and analysis of many igneous rock samples.

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Evolution of the Gecko Corridor, Tennant Creek Goldfield

Ana L Cuison1,2, Grant A Osborne3 and Robert T Bills3

Since 1928, gold, copper and bismuth have been produced from the Tennant Creek Mineral Field (TCMF). The mineralisation is associated with hydrothermal iron oxide bodies, composed of varying proportions of magnetite, haematite, quartz, chlorite, sericite and sulfides, that are locally termed ‘ironstones’. These bodies occupy linear belts known as corridors, lines-of-lode, or mineralised trends, and are commonly enveloped by a narrow alteration zone, comprising chlorite and magnetite, or less commonly, dolomite and tacle (Ahmad et al 2009).

The ironstones are documented as being emplaced prior to the Au-Cu-Bi mineralisation event (Skirrow 2000) and despite intense exploration by many explorers over time, the vast majority and indeed all of the economic mineralisation has only ever been discovered within close proximity to ironstones, ensuring they have become an essential ingredient within local Au-Cu-Bi exploration models. Indeed, the relationship is viewed so strongly that exploration has seldom strayed from the productive corridors into areas without known ironstones, ensuring that the relationship has become a ‘self-fulfilling prophesy’. The reason for the lack of faith in non-ironstone-associated mineralisation is not clearly understood. If the ironstones are simply providing a geological and/or chemical trigger for Au-Cu-Bi deposition from later mineralising fluids, then mineralisation is not clearly understood. If the ironstones are simply providing a geological and/or chemical trigger for Au-Cu-Bi deposition from later mineralising fluids, then other types of Au-Cu-Bi mineralisation should theoretically occur in suitable settings not occupied by ironstones, for example dilation zones along favourably oriented structures. This abstract briefly reviews current ideas on the evolution of the TCMF using the Gecko Corridor as an example.

Emmerson Resources Ltd (ERM) began exploring in the TCMF in 2007 and inherited a vast legacy of historical data from the main explorers (viz Peko Ltd, Australian Development Ltd, Normandy Poseidon Ltd, North Flinders Mines Ltd, Roebuck Resources NL and Giants Reef Mining Ltd). Initially, ERM did what newcomers to the field have traditionally done, opting for brownfields exploration along mineralised corridors, but very soon realised that previous explorers had been very efficient and that a strategy designed to exploit their oversights was doomed to failure. The keys to success in areas of mature exploration history through time inevitably rely on one, or more of a select few factors (Trench 2013):

1. Finding clues in existing data that others have missed before (data mining).
2. Creating entirely new datasets (enlarging the search space), or redefining them geochronologically.
3. Benefiting from increased commodity prices or mineral beneficiation processes (right place at the right time).

The key frustrations to exploration within the TCMF have been the absence of an agreed age for the mineralisation and of a tectonic setting that successfully integrates the observed lithologies with the mineralisation occurrences; together, these form a major hurdle to a robust predictive targeting model. ERM soon recognised several key areas for further work to address these issues and initiated academic research. Large areas of the ERM tenement block lie under recent cover, predominantly windblown sand and colluvium, which together with a varied weathering profile (commonly 80 m deep but locally up to 200 m), reduce the efficiency of geochemical exploration and may adversely impact geophysical techniques. Nevertheless, in order to be able to successfully explore for other mineralisation styles within the TCMF, a sound understanding of the structural geology and the age of the mineralising event, is vital to selection of the appropriate exploration prospecting tool.

Geological mapping (eg Donnellan et al 1995) is largely confined to WNW-trending outcrop ridges, best exposed in the eastern and northern-central parts of the TCMF, separated by alluvial/fluviatile sheetwash deposits. Donnellan (2005) proposed a regional correlation between the host Warramunga Formation and the Ooradidgee Group, which mainly outcrops to the SE in the Murchison and Davenport Ranges and to the NW in the Short Ranges, and the felsic Tennant Creek Supersuite (TCS). Published geochronology is dominated by magmatic zircon ages from the granitoids/porphyries of the TCS (ca 1850 Ma; Wyborn 2001) and from volcanic rocks within the Ooradidgee Group (ca 1840 Ma; Maidment et al in press), with far fewer volcanic or detrital zircon dates from within the Warramunga Formation (1872 ± 9 Ma; Wyborn 2001). ERM have specifically targeted geochronological investigations

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in intermediate-mafic intrusive rocks, deformed granitoids and Warramunga Formation sedimentary units in an effort to constrain the geotectonic setting. Preliminary results from current research (M Hill, University of Western Australia, pers comm 2012) into the geochronology of the different intrusions in the TCMF show that the intermediate-mafic intrusive rocks occupy a narrow age range of 1851–1854 Ma, slightly older than the 1847 Ma age of the quartz-feldspar porphyries reported by Maidment et al (in press), but both lie within the range of ages attributed to the TCS granitoids (1858–1840 Ma; Wyborn 2001). Based on cross-cutting relationships, it is interpreted that the intermediate-mafic intrusive rocks are coeval with, and probably represent a more primitive variant of the TCS.

These preliminary results, coupled with those of Maidment et al (in press), coincide with the readjusted age for the Tennant Creek Au-Cu-Bi mineralisation (1851–1847 Ma) reported by Fraser et al (2008), supporting the proposition that the mineralisation is related to the TCS and is not related to younger bimodal volcanism and shallow-level intrusions of the Treasure Suite (ca 1820 Ma), as advocated by Wyborn et al (2001).

Crohn and Oldershaw (1965) recognised that the mineralised shears hosting ironstone ± Au-Bi-Cu within the Tennant Creek One Mile mapsheet area predominantly trend west, but also trend WNW or ENE. The most abundant (often barren) shears trend NW or NE and are typically quartz-filled, while additional minor sets of shears trend NNW and NNE. This is supported by statistical analysis of lineament orientations from a dataset covering the larger Tennant Creek 250k mapsheet area (Johnson and Donnellan 2001). Analysis of underground structures at the Gecko Mine within the Gecko Corridor reveals they are a fractal subset of the this dataset, with the most commonly occurring orientation trending 120–125°.

Assessment of detailed oriented structural logging from 3 drillholes into adjacent shear zones at the Goanna prospect reveals that veiniform Cu-mineralisation in the Central Shear Zone (CSZ) has a dextral sense, whereas Au-Cu-Bi mineralisation associated with small ironstone bodies in the Southern Shear Zone (SSZ), located 65 m to the south, has a sinistral sense. A dextral sense was also observed at the Monitor prospect, where petrographic work has confirmed that veiniform Cu overprints early pyrite-Au (Purvis 2012a).

Based on the above observations and constrained by the new geochronology cited above, the following geological evolution of the TCMF is proposed:

1. **D₁**: Rifting of an unknown basement prior to 1858 Ma triggers deposition of Warramunga Formation sediments into WNW–west-trending basins. Sediments were deposited from a dominantly felsic volcanic source region located to the east and south, although mafic intrusive rocks may also have been important. Synsedimentary quartz porphyry sills intruded locally (McPhie 1994).

2. **D₂**: N–S compression resulted in basin inversion and bedding-parallel thrusting of the Warramunga Formation sediments about E–W axial planes. Circulating basal brines leached iron from the sedimentary pile, which was redeposited as tabular ironstones within axial planar shears, or by selective replacement of bedding plane thrusts in axial hinge zones of folds.

3. **D₃**: The TCS was emplaced at 1851–1847 Ma, causing local doming and steepening existing faults. Granites and quartz porphyries were volumetrically predominant, whereas minor, more primitive intermediate-mafic intrusions are located in pre-existing major structures.

4. **D₄**: Transcurrent shearing followed soon after granite emplacement and prior to solidification. An early sinistral phase was responsible for the deformation/brecciation of the ironstones and was accompanied by Au-Cu-Bi mineralisation. Subsequent minor dextral reactivation was accompanied by, or remobilised existing Cu mineralisation.

It is possible that all of the proposed events (D₁–D₄) form part of continual deformation during the Tennant Creek Event, and hence, that the mineralisation is both coeval with the TCS and syntectonic.

Aeromagnetic and ground magnetic surveys in the 1950s and 1960s led to the identification of strong magnetic signatures that were shown by drilling to be caused by ironstones and led to the discovery of gold-copper-bismuth deposits. One such signature delineates the Gecko Corridor, which contains a number of magnetic anomalies (numbered AN1 to AN6), trending WNW (see Figure 1). Subsequent development and mining of some of these anomalies led to the discovery of additional ironstones (K44, L25 and R54: Richards 1999).

In 2011, ERM flew helicopter-borne electromagnetics (HeliTEM), as well as conducting ground and down-hole electromagnetic surveying along the Gecko Corridor. HeliTEM generated an excellent dataset for defining significant and minor structures that have undergone intense alteration, indicative of shear zones. The combination of these results with ground Induced Polarisation (IP) surveys and 3D integration of geology led to the discoveries of the Goanna and Monitor prospects, located close to the existing underground development (Bills 2012; see Figure 1).

Images of Vector Residual Magnetic Intensity covering the Gecko Corridor show that the Gecko mine anomalies are centred on discrete oval magnetic highs. The Goanna shear zones lie to the east, just outside the margin of the main magnetic high, whereas the Monitor prospect lies along the margin of an elongate magnetic high to the west.

Gravity surveying over the Gecko Corridor shows that the majority of the Gecko magnetic anomalies, including Goanna and Monitor, lie in a gravity low in the Bouguer anomaly map, except for two positive gravity anomalies that correspond to the shallow AN2 and AN4 ironstones. It is interpreted that the gravity low reflects intense weathering of the Gecko Corridor overlying the deeper ironstones (AN3, AN1 and AN1A).

Pole-Dipole IP traverses and a larger gradient array survey were completed, with the aim of ranking the identified HeliTEM anomalies and defining potential
targets, as well as aiding in structural mapping. Targeted exploration drilling resulted in the identification of additional shear zones at Goanna: the Far Northern Shear Zone (FNSZ) and FNSZ-1.

Metal zonation within the Gecko Corridor is characterised by copper and bismuth in its central part, with localised gold pods at the bottom (AN2) and top of ironstones (K44, AN1). Copper enrichment occurs on the northern margins of these ironstones. To the west is the Cu-rich, Au-poor AN4 ironstone, while the Monitor prospect is copper-gold-bismuth rich without ironstone. To the east is the Cu-rich Goanna prospect, with localised gold-bismuth pods.

Detailed geologic, metal zonation and paragenetic studies have been undertaken at the Monitor and Goanna discoveries. The Goanna prospect consists of several WNW-trending shear zones, varying in width from 2 m to 20 m, and extending 250 m to 700 m along strike. Mineralisation is hosted by sandstone and siltstone of the Warramunga Formation.

The ores and ironstone within the Southern Shear Zone (SSZ) are hosted by intensely chloritised sandstone and siltstone. Ironstones in the SSZ are massive lenticular bodies composed of haematite (specularite)-magnetite ± chlorite. The ironstone underwent brittle deformation, manifested as cracks, fractures and breccia zones infilled by sulfides, chlorite and locally by quartz, confirming that mineralisation postdates ironstone formation. The SSZ is characterised by an intense chlorite alteration halo that extends up to 20 m along the shear zone, but less than 2 m away from the margins of the ironstones/shear zones. Early chlorite alteration occurred during ironstone formation and continued to occur during sulfide deposition. Pervasive chloritisation, with associated magnetite-haematite as disseminations/replacements and stringers, occurs on the apophyses of the ironstone. The chlorite-talc alteration zone is best developed in the upper portion of the shear zones. Extending outward from the chlorite-sericite alteration zone is a zone of dolomite–quartz alteration, forming a mantle above the ore zone.

The ore zone (>4% Cu) in the SSZ occurs within and above the ironstone. Chalcopyrite and pyrite comprise the bulk of the sulfides, occurring as breccia fill/cement within the brecciated specularite-haematite ironstone, or locally as distinct veins. Gold is found at the base and top of the ironstone as discrete pods. Outside the ironstone, chalcopyrite occurs as monomineralic veins and stringers within an intensely chloride-altered sedimentary unit. The chalcopyrite veins lack alteration haloes, suggesting that the causative fluids were in chemical equilibrium with their altered host rocks.

In contrast, the majority of the ore zone within the Central Shear Zone (CSZ) and Northern Shear Zone (NSZ) is hosted in chlorite-altered siltstone cut by quartz-chalcopyrite-pyrite-chlorite veins. Copper sulfides occur as massive blebs in quartz. The quartz occurs as either stockworks, veins or as breccia cement. Gold occurs as inclusions in chalcopyrite (Purvis 2012b) in the NSZ. Bismuthinite occurs as aggregates within the quartz veins and is locally associated with chalcopyrite.

It is interpreted that the Gecko Corridor represents an original basin-bounding fault that was active during deposition of the Warramunga Formation. It was subsequently reactivated during basin inversion and transcurrent deformation during the Tennant Event (Maidment et al in press). Ironstones developed within the corridor during basin inversion, and Au-Cu-Bi mineralisation was controlled by a combination of physical and chemical conditions that are optimal around the edges and within the brecciated margins of these ironstones.

Figure 1. Plan view of Gecko Corridor showing location of Goanna and Monitor prospects in relation to historically mined and remaining ore bodies and underground access at Gecko mine.
Exploration to date in the TCMF has concentrated on Au-Cu-Bi mineralisation associated with hydrothermal ironstones, but the recognition of a new mineralisation style in the Gecko Corridor, using an integrated geological and geophysical approach, has raised the possibility that more non-ironstone-hosted mineralisation will be discovered by those bold enough to explore other ideas.

The ERM exploration model is based on understanding the fundamentals of the mineralising process and its fingerprints, and on regional- and deposit-scale structural interpretations to identify the controls of the copper-gold mineralisation. Additional studies are also being undertaken with the aim of characterising the alteration around mineralisation in the Gecko Corridor, using hyperspectral instruments. This approach aims to map the alteration footprints and zoning of mineral assemblages, and to provide enhanced vectoring capabilities at both regional and local scales within the TCMF.

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Spectral reflectance characteristics of type example rocks from the Tennant Creek Mineral Field

Belinda R Smith1, Jon F Huntington2 and Georgina A Gordon3

The Tennant Creek Mineral Field is an historically important part of the Warramunga Province of the Tennant Region in the Northern Territory, having produced over 4 Moz Au, 345 000 t Cu, 1.8 Moz Ag and 14 000 t Bi (Ahmad et al 2009) since its discovery in the 1930s. High-grade mineralisation is hosted in discordant ironstone pods and in hydrothermally altered metasedimentary rocks adjacent to and below the ironstones. Ore and gangue mineral zonation is characteristic, although the zonation may vary between orebodies. The economic significance of the mineral zonation is known and these alteration minerals can be mapped using the HyLogging™ technology.

Type example rocks from the Tennant Creek Mineral Field were sourced from Data Metallogenica (DM) plates and from trays of representative core supplied by Emmerson Resources Ltd (Emmerson), an active explorer in the area. Emmerson compiled the samples to assist new geologists to become familiar with typical Tennant Creek lithologies, textures and alteration, and to showcase the variations for display purposes. These samples were made available to NTGS for hyperspectral scanning and imaging with the HyLogger 3-7 instrument in December 2011.

The representative samples were subdivided into the following groups after scanning:
1. Sedimentary rocks, labelled ‘unaltered sandstone’ or ‘chlorite-altered siltstone’ etc.
2. Ironstones, labelled ‘ironstone’ ‘haematite rock’, ‘magnetite rock’ or similar.
3. Intrusive rocks, including ‘chlorite porphyry’, ‘mylonitic granite’ and ‘gabbro-norite-pyroxenite’.
4. Alteration rocks, including rocks with appreciable talc, dolomite and chlorite that are characteristic of the alteration mineral zonation around the ironstone pods that may host mineralisation. They include ‘talc dolomite’, ‘talc chlorite’ and ‘chlorite rock’, and may have relict sedimentary textures such as foliation.

Some observations from the hyperspectral scanning include:

- Lithology nomenclature does not always reflect mineralogy. For example, the sample described as, ‘chlorite-altered siltstone’ contains very little or no chlorite, but has a green tinge that suggested the presence of chlorite.
- Rock samples with similar names can have quite different mineralogy (such as ‘talc chlorite’ samples).
- The ‘ironstone’ lithologies did not show any uniformity in the Visible Near Infrared (VNIR) or Shortwave Infrared (SWIR) response, and were often noisy or ‘aspectral’ in the SWIR. However, the Thermal Infrared (TIR) response shows that such samples could be broadly separated into ‘quartz’ ironstones and ‘chlorite’ ironstones. Both the ‘quartz’ ironstones and the ‘chlorite’ ironstones could be mineralised.

The major implication from this work is that further divisions of lithologies (such as ironstones into ‘quartz-rich’ and ‘quartz-poor’ types) is possible, which may show distribution patterns that have not been previously recognised. Using averaged spectra from ironstone samples, it may be possible to spectrally match ironstones when other visual features are not apparent, although this work is still at an early stage. More care may be needed when logging the chlorite alteration of green metasedimentary rocks, as chlorite may not be present and the rocks can give a false impression of proximity to alteration if only visually logged.

An outcome from this work is an atlas designed to be a visual record of core imagery and reflectance spectra of type example rocks, including data available in TSG format (Smith et al. 2013). The atlas’ spectral data can be used to compare and contrast spectra between datasets to assist in understanding variations that may not be discernible from visual logging alone. This is a first-stage edition of an atlas, with future versions containing further representative samples, with more detail and examples of spectral matching from the atlas to Tennant Creek drillholes. The study suggests there is considerable scope to create similar district-specific atlases to help geologists integrate mineral spectroscopy data with their conventional logging goals.

**Reference**


**Overview of the geology and mineral and petroleum resources of the McArthur Basin, NT**

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The Palaeo- to Mesoproterozoic McArthur Basin in the northeastern Northern Territory, unconformably overlaps Palaeoproterozoic basement rocks of the Pine Creek Orogen, Murphy Province and Arnhem Province (Figure 1). The Murphy Inlier of the Murphy Province was probably a palaeogeographical high separating the McArthur Basin to the north from the South Nicholson Basin and Lawn Hill Platform to the south (Plumb and Wellman 1987, Wygralak et al. 1988). To the southeast, McArthur Basin stratigraphy extends to the Isa Superbasin in Queensland. Phanerozoic strata of the Georgina, Carpentaria and Arafura basins unconformably overlie the McArthur Basin succession, which continues under cover to the Tomkinson Province of the Tennant Region, and probably to the Birrindudu Basin further west.

Several models involving extensional tectonics have been proposed for the initiation and evolution of the McArthur Basin (eg Plumb and Derrick 1975, Plumb et al 1980, 1990, Plumb and Wellman 1987, Etheridge and Wall (1994), Rogers (1996), Leaman 1998). These models relied largely on macroscopic fault and lineament trends, and largely varied on the orientation of extensional and contractual phases (Rawlings et al 2004). Specific fault orientations acted as normal or growth structures, or as accommodation or transfer features during various stages of basin formation. The extensional nature of the models proposed was simplistic and largely framed around the presence of significant volcanic and coarse-grained clastic rocks at the base of the basin succession. Alternatively, Scott et al (2000) and Rawlings (2002) used facies architecture, geochemistry, geophysics and geochronology to model a convergent tectonic setting inboard an active southern margin to the North Australian Craton.

The basin architecture has been modelled as several north-trending asymmetric rifts or grabens separated by transverse faults/ridges. Previous workers identified two north-trending troughs (Walker and Batten troughs),

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4 The Spectral Geologist™ software
separated by the east-trending Urapunga Tectonic Ridge (eg Plumb and Derrick 1975, Plumb et al 1980, 1990, Plumb and Wellman 1987). Tectonically ‘stable’ shelves flanked these troughs. However, more recent studies (Rawlings et al 1997, Rawlings 1999, Rawlings et al 2004), and in particular a deep seismic reflection survey across the Batten ‘trough’ (Rawlings et al 2004), do not support this architecture. The seismic survey showed that the Batten ‘trough’ is a fault zone rather than a primary depositional feature, and that a thick (8 km), relatively flat-lying stratigraphic succession extends beyond its margins (Rawlings et al 1997, Rawlings 1999, Rawlings et al 2004). Similarly, the Walker Trough is now interpreted as a fault zone, and the previously described ‘shelves’ are now described as geographic components (Figure 1). The Beetaloo sub-basin is not exposed and is obscured by cover of the Carpentaria and Georgina Basins.

The McArthur Basin contains an unmetamorphosed and relatively undeformed succession of sedimentary and minor volcanic rocks, with a preserved thickness of up to 10 km (Plumb and Wellman 1987). There have been two broad approaches to subdividing the successions of the McArthur Basin and correlative terranes (Isa Superbasin, Lawn Hill Platform, Murphy Province): a sequence stratigraphic approach by Jackson et al (1999, 2000) and Southgate et al (2000); and an alternative scheme promoted by NTGS that subdivides the entire McArthur Basin succession into five basin-wide, non-genetic ‘packages’ (Rawlings 1999). These depositional packages are disconformity or unconformity bounded and each is characterised by similarities in age, stratigraphic position, lithofacies composition, style and composition of volcanism, and basin-fill geometry (Figure 2). There is common recognition that depositional cyclicity in the McArthur Basin succession was driven predominantly by episodic tectonism.

The McArthur Basin is one of the most significant base metals provinces of Australia and forms part of the Carpentaria Zinc Belt, which hosts a number of significant base metals deposits, including Mount Isa, Hilton, George Fisher and Century in Queensland, and McArthur River (formerly HYC: ‘Here’s Your Chance’) and Myrtle in the Northern Territory. The McArthur Basin hosts over three hundred mineral occurrences including base metals (lead, zinc, silver, copper), uranium, iron ore, manganese, barite and phosphate. Diamondiferous kimberlite pipes intruded

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**Figure 1.** Geological setting of McArthur Basin (slightly modified after Rawlings 1999). Position of southern McArthur Basin deep seismic line (Rawlings et al 2004) shown by solid red line.
the succession during the Palaeozoic. Localised historic mining has occurred since the early 1900s, but significant mining activity has taken place only at McArthur River (base metals), Merlin (diamonds) and Redbank (copper).

Palaeoproterozoic

Redbank Package

The Redbank Package (Rawlings 1999, 2007) is up to 6 km thick and represents the basal succession of the McArthur Basin. It is characterised by shallow-marine to fluvial sandstone, and lesser volcanic rocks and shale. All units have well defined minimum ages of 1710 Ma, but poorly constrained maximum ages. This package hosts Cu in breccia pipes at the Redbank and Running Creek Fields near the southern edge of the basin. Vein-type Cu, comprising secondary Cu minerals in fractures and shears, appears in lower volcanic units in the south. Five types of small U and U-Au deposits have been identified near the base of the package around the Murphy Inlier, as well as on the western margin near the contact with the underlying Pine Creek Orogen.

Goyder Package

The Goyder Package is largely present in the Walker Fault Zone, where it separates the Redbank and Glyde packages. It ranges in age from 1710 to 1670 Ma (Rawlings 1999), constrained by overlying and underlying volcanic units, and comprises dominantly sandstone and siltstone deposited in shelf, sabkha, shallow marine and possibly braided fluvial environments.

Glyde Package

The Glyde Package mainly comprises an up to 5 km-thick succession of evaporitic carbonate, mudstone and sandstone, interpreted as shallow- to moderately deep water and locally emergent. Evidence of syndepositional fault movement is common and may be responsible for the generation of local and regional hiatuses within the package. The age of the Glyde Package is constrained by U-Pb SHRIMP zircon ages ranging from 1640 Ma to 1600 Ma. The prospective McArthur Group of this package hosts numerous stratiform base metals deposits.
in the Batten Fault Zone, the largest of which is the world-class McArthur River Mine. The McArthur Group is also prospective for Century-style base metals deposits, and its lower part hosts some vein-style, chalcopyrite-rich base metals deposits, and vein-style Cu. The McArthur Group contains proven source rocks for oil and gas, with three formations containing TOC up to 8%.

Mesoproterozoic

Favenc Package

The Favenc Package comprises a regionally extensive 50–1600 m-thick succession of stromatolitic dolostone–sandstone, deposited in a shallow-water, marginal-marine, peritidal-shelf and/or continental-sabkha environment (Rawlings 1999), and local mafic volcanic rocks. The age of the Favenc Package is constrained by SHRIMP zircon dates of 1613 ± 4 Ma and 1589 ± 3 Ma (Page et al 2000).

Wilton Package

The Wilton Package (Roper Group) comprises a upward-coarsening cyclic succession of mainly marine mudstone alternating with sandstone. Its maximum age is constrained by an Rb-Sr determination of 1429 ± 31 Ma for diagenetic illite (Kralik 1982) and a SHRIMP U-Pb zircon date of 1492 ± 4 Ma for a tuffaceous bed (Jackson et al 1999). A minimum age of 1324 ± 4 Ma comes from SHRIMP dating of baddeleyite from dolerite (Abbott et al 2001). The unconformity at the base of the Roper Group is considered to be related to the Isan Orogeny (1580–1560 Ma) and Jackson et al (1999) estimated a break in deposition of 80–90 My. The Roper Group hosts several significant JORC-compliant resources of massive oolitic to pisolithic iron ore within a single formation in the central eastern part of the basin. The succession also has potential for heavy minerals deposits related to regolith developed on ilmenite-bearing dolerite. In the Beetaloo Sub-basin, recent exploration indicates there is significant potential for unconventional hydrocarbons in the Roper Group stratigraphy.

Mineral and petroleum potential

The McArthur Basin is widely recognised as a significant stratiform base metals province, but also has recognised occurrences and is prospective for other mineralisation styles and commodities. Deposit types include: (a) stratiform, sedimentary base metals deposits hosted in pyritic organic rich shale and siltstone (eg McArthur River); (b) stratabound, discordant base-metals deposits (eg Coxco, Cooley and Ridge); (c) copper-bearing breccia pipes (eg Redbank); (d) copper in shear zones and veins; (e) uranium deposits within sandstone or volcanic rocks (eg Westmoreland deposits); (f) stratiform oolitic ironstone occurrences within the Sherwin Formation (eg Roper River iron ore); (g) irregular manganese occurrences associated with the Karns Dolostone and Echo Sandstone (eg Calvert Hill deposits); (h) sedimentary phosphate occurrences within the Echo Sandstone/Karns Dolostone; and (i) hard-rock heavy-minerals concentrations in dolerites, and associated eluvial and colluvial deposits. The McArthur Group is also considered prospective for Century-style base metals deposits, and the McArthur Basin, in particular Roper Group rocks in the Beetaloo Sub-basin, and the McArthur Group, is also prospective for petroleum.

Stratiform Zn-Pb-Ag deposits comprise fine-grained pyrite, galena and sphalerite, preferentially concentrated in pyritic bituminous shale. The deposits are stratiform and stratabound, with the HYC Pyritic Shale Member of the Barney Creek Formation (McArthur Group) hosting the only known economic occurrences. They are considered to have formed either synchronously with sedimentation at the sediment–water interface or by early diagenetic processes, involving low-temperature hydrothermal fluids. Unlike Mount Isa, the currently known deposits in the McArthur Basin are unmetamorphosed, and at McArthur deposit the sulfides are consequently extremely fine-grained and seldom exceed 10 μm. The McArthur River mine has a total resource of 162.2 Mt at 10.7% Zn, 4.7% Pb and 48 g/t Ag; total reserves are recorded as 49.6 Mt at 9.6% Zn, 4.2% Pb and 43 g/t Ag. At the Myrtle prospect, 20 km south of McArthur River, the mineralisation is coarser, with an inferred resource of 43.6Mt at 4.09% Zn and 0.95% Pb, at a 3% Zn+Pb cutoff, with a higher-grade core of 15 Mt at 5.45% Zn and 1.0% Pb.

Discordant Pb-Zn-Ag+Cu deposits occur as open space-filling of coarse-grained pyrite, galena and sphalerite + chalcopyrite in brecciated dolostone, and were generated by low- to moderate-temperature hydrothermal fluids. A number of these are associated with karstification close to silicified regolith, with the brecciation produced by hydraulic fracturing. Many are regarded as classic Mississippi Valley-style deposits. The Umbolooga Subgroup (McArthur Group, Glyde Package) contains almost all of these deposits, with the majority occurring in the Reward or Emmerugga dolostones. Vein-style deposits are chalcopyrite-rich and were probably produced by moderate-temperature hydrothermal fluids. They are few, and are generally confined to the lower McArthur (Glyde Package) and Tawallah (Redbank Package) groups.

Copper-bearing breccia pipes are known from the Redbank area (Figure 1) near the southern edge of the southeastern McArthur Basin. The breccia pipes are steeply plunging cylindrical structures, 4–75 m in diameter, with a vertical extent of at least 330 m. Most pipes are within the Gold Creek Volcanics, but in an area close to Wollogorang Station, pipes are also known from within the Wollogorang Formation and Settlement Creek Dolerite (Tawallah Group, Redbank Package). Over 50 breccia pipes are known from the Redbank area and at least 10 of these contain copper mineralisation, with chalcopyrite as the main primary mineral. The pipes comprise various proportions of microbreccia, dolomite, quartz, chlorite, celadonite, haematite, K-feldspar and apatite, with minor barite, rutile and galena. Copper is normally the only commodity present in economic concentrations; however, anomalous Co concentrations
are known, and some pipes to the north also contain significant Ni and Co (eg Rawlings 2006). Total Indicated and Inferred JORC resources for the Redbank project area are 6.24 Mt at 1.5% Cu for 95 900 t of Cu.

Vein-type copper occurs in veins and fault infills. Production from these veins has been insignificant and there have been no detailed studies of this deposit type.

Uranium (+gold+PGE) occurs in a number of small uranium-gold deposits in the basin adjacent to the Murphy Province. Most prospective occurrences of this group that have an established resource (Westmoreland uranium deposits) are in adjoining areas of Queensland. Almost all of the occurrences are in the Westmoreland Conglomerate and Seigal Volcanics (Tawallah Group, Redbank Package) and in adjacent, unconformably underlying older rocks. Several occurrences of uranium (+gold+PGE) are also known within the Kombolgie Subgroup (Tawallah Group, Redbank Package) on the northwestern margin of the McArthur Basin. The largest-known deposit of this type, Eva, has a JORC compliant total resource of 650 t U3O8 in ore grading 0.12% U3O8 and 380 kg Au in ore grading 3.77 g/t Au (NuPower 2011).

Iron ore is hosted in several formations of the Roper Group (Wilton Package) and is also known from the Nathan Group (Favenc Package). The major host is the Sherwin Formation of the Roper Group. Sherwin Formation ironstone typically comprises lenses of massive oolitic to pisolithic beds, interbedded with medium- to very coarse-grained ferruginous (chamosite-siderite at depth) sandstone, sandy mudstone and shale. The ore comprises closely packed ooids (0.5–5 mm in diameter) of soft red haematite and goethite, and varying amounts of well rounded quartz grains. Several large projects are presently under assessment in the Sherwin Formation; for example, the Roper Bar Project (Western Desert Resources Ltd) has a JORC-compliant Resource estimate of 402 Mt at 40.0% Fe, 28.0% SiO2, 2.5% Al2O3, 0.005% P and 9.7% LOI, including a global direct shipping ore (DSO) component of 32.1 Mt at 56.8% Fe (WDR 2012). The Roper River project (Sherwin Creek and Hodgson Downs; Sherwin Iron Ltd) has Indicated and Inferred Resources of 488 Mt at 41.7% Fe, including a higher-grade component at 33.8 Mt at 57.4% Fe, 12.8% SiO2, 1.6% Al2O3, 0.05% P and 2.6% LOI.

Several iron occurrences are known from the basal part of the Mallapunyah Formation (Tawallah Group, Redbank Package). The largest reported occurrence is at the Tawallah Range prospect, where two haematite-rich lodes contain some 12 Mt of iron ore averaging 37–40% Fe (Johnston 1974).

Small manganese occurrences, hosted in chert and dolostone assigned to the Karns Dolostone of the Nathan Group (Favenc Package), are known from the southeastern McArthur Basin.

Massive to flaggy phosphate beds with grades in the range 5–24% P2O5 andstromatolitic phosphate uniformly around 29–34% P2O5 occur locally in the basal, unconformity-bound Karns Dolostone (Nathan Group, Favenc Package).

A number of diamond deposits are known from the McArthur Basin area, including the significant Merlin and E.Mu pipe deposits. These diamond occurrences belong to geologically younger intrusive events (ca 367–360 Ma, Carboniferous) located within the McArthur Basin geographic region. The combined Probable Ore Reserve for all (14) diamond pipes at Merlin is 11.1 Mt at 0.26 carats per tonne (ct/t) for a total of 2.89 Mct, and the Indicated and Inferred Mineral Resource is 19.02 Mt at 0.24 ct/t for a total of 4.31 Mct.

The McArthur Basin has long been recognised as having potential for petroleum (eg Muir et al 1980) and both oil and gas are known to have flowed from petroleum wells and mineral exploration drillholes. To date twenty-eight wells have been drilled across the Basin. Small oil shows are locally abundant and extensive bitumen/pyrobitumen has been reported from numerous intervals within the succession, from overlying Palaeozoic rocks, and even from breccia pipes that penetrate the succession in the Redbank area (Knutson et al 1979). Despite the Proterozoic age of the succession, proven source rocks are present - Crick et al (1988) recognised five potential source rocks in the McArthur Basin, defined as having total organic carbon (TOC) greater than 0.5%. These include intervals within the Barney Creek, Lynott and Yalco formations of the McArthur Group (Glyde Package), and the Velkerri and Kyalla formations of the Roper Group (Favenc package). Of these, the Barney Creek and Velkerri formations have the highest TOC values, ranging up to 8% and 12%, respectively (Crick et al 1988, Langian et al 1994, Falcon 2009).

Large parts of the McArthur Basin are relatively undisturbed structurally and have not been subjected to significant heat/stress regimes, and hence are regarded as being prospective for conventional and more particularly, for unconventional resources. The McArthur and Roper groups are recognised as having the most petroleum potential. Maturation levels in the McArthur Group vary from marginally mature to overmature and hydrocarbon generation is considered to have occurred prior to deposition of the Roper Group (Crick et al 1988, Jackson et al 1988). Roper Group source rocks vary in maturity from below to above the oil window (eg Crick et al 1988), with hydrocarbon generation occurring during the late Mesoproterozoic (Dutkiewicz et al 2007) and possibly in the early Palaeozoic (Jackson et al 1988).

In relatively recent times interest has focused on the Roper Group within the Beetaloo Sub-basin (eg Langian et al 1994, Silverman et al 2007), and on the McArthur Group in the Glyde sub-basin of the Batten Fault Zone (Armour Energy 2012).

In the Beetaloo Sub-basin the Roper Group reaches a thickness of about 3000 m in the main depocentre. Source-rock successions are in the oil window over large areas of the sub-basin and are probably gas mature in the main depocentre (Ambrose and Silverman 2006). The oldest source rocks (Velkerri Formation) are widespread across the sub-basin and have TOC values between 1 and 3%, with maximum recorded values of 8–12% (eg Falcon 2009). The stratigraphically higher Kyalla Formation is more restricted in extent, with TOCs are generally less than 2%, but range up to about 9% (Jackson et al 1988). Oil and gas shows are
common within both the Velkerri and Kyalla formations, with numerous reports of strong odours, and gas and oil ‘bleeds’ (Silverman et al. 2007).

In the Glyde sub-basin of the Batten Fault Zone, recent drilling by Armour Energy Ltd (Glyde-1 and Glyde-1 lateral) encountered gas-bearing formations in the Barney Creek Formation and Coxco Dolostone of the McArthur Group (Glyde Package) at about 500m depth (Figure 2). The Glyde-1 vertical well data provides further evidence that the Barney Creek Formation is a source rock for Coxco Dolostone Member gas accumulations and has the potential for a sizeable unconventional gas resource. Based on assessment of the Coxco Dolostone member from the lateral well, Armour estimates the Greater Glyde River field to hold a Mean Prospective Conventional Gas Resource of 130.7 BCF.

References


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**Unconventional prospectivity: Unconventional hydrocarbon resources in Australian basins, with a case study from the Georgina Basin.**

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**Introduction**

Exploration for unconventional hydrocarbons has transformed the petroleum industry in Australia. It has seen the growth of the fledgling Coal Seam Gas (CSG) industry into a major supplier for the eastern energy market, and an exploration boom in shale and tight gas in Australia’s onshore basins. The first successful flow from a shale gas well in the Cooper Basin in 2011 has been followed by the first shale gas production from the basin in 2012, and a series of discoveries in other sedimentary basins across Australia. Although much of the activity has been in basins with proven potential for conventional hydrocarbons and coal, unconventional hydrocarbon exploration is increasingly targeting frontier basins.

As part of an unconventional prospectivity assessment of Australia’s onshore basins by Geoscience Australia, new geological studies have commenced in the Georgina Basin, including new biostratigraphic work, geochemical sampling and analysis and a GIS project. These new data will contribute to a formal unconventional resource assessment.

**Unconventional hydrocarbons in Australia**

In Australia, current unconventional hydrocarbon resources of interest to exploration include CSG, shale gas and oil, and tight gas and oil.

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Currently, most CSG resources are located in the eastern Australian sedimentary basins (Figure 1) and are hosted within fluvio-lacustrine coal measures, including Permian coal measures of the Bowen, Galilee, Sydney, Gunnedah, Gloucester and Cooper basins; Jurassic Walloon Coal Measures of the Surat and Clarence-Moreton basins; the Triassic Nymboida and Ipswich basins (underlying the Clarence-Moreton Basin); and Cretaceous Maryborough and Eromanga basins. Potential CSG resources are also associated with coals in the Pedirka, Arckaringa, Perth and Canning basins in central and Western Australia. Geological differences between the coals have implications for the methods required to extract CSG. For example, the Bowen Basin Permian coals have higher gas contents, due to their higher rank, than overlying Jurassic counterparts in the Surat Basin. However, the younger Jurassic coals often achieve a higher gas (and water) flow due to their greater porosity and permeability (Draper and Boreham 2006).

Shale gas and oil are hydrocarbons generated within organic-rich, fine-grained rocks, including shale, mudstone, siltstone and marl, that have been trapped therein or migrated a very short distance to juxtaposed and interbedded lithologies, eg fine-grained sandstone, limestone and dolostone. As with CSG, shale gas may be thermogenic or biogenic in origin. The term ‘oil shale’ generally refers to organic and fine-grained, oil-prone source rocks that are thermally immature for hydrocarbon generation and is, thus, distinct from ‘shale oil’. The use of the term ‘light tight oil’ (IEA 2012) distinguishes this liquid hydrocarbon from shale (kerogen) oil and from other abundant unconventional oils, such as the heavy oils from tar sands and bitumen deposits. Shale gas, shale oil and tight gas potential is distributed across a number of Australian basins, some of which are also associated with significant conventional petroleum potential (Figure 2). The age of target formations varies widely from the Mesoproterozoic of the McArthur Basin, to the Cambrian–Ordovician of the Amadeus and Georgina basins, the Permian of the Arckaringa and Perth basins, and the Cretaceous of the Eromanga Basin. Target formations for shale gas and tight gas in eastern Australian basins include the Permian Cooper and Bowen basins, and the Jurassic–Cretaceous Gippsland and Otway basins. The ages of these basins contrast with those of many of the producing shale gas basins of North America, which are predominantly Devonian, Carboniferous and Cretaceous, and also with the dominantly Silurian shale gas basins of eastern Europe.

Prospectivity in Australia

Australia’s total unconventional hydrocarbon resource endowment is poorly constrained. Currently available national resource estimates have very large associated uncertainties and, in the case of shale and tight gas, are only based on a partial assessment of selected basins. Geoscience Australia, is working with its counterparts in the States and Northern Territory, to assess Australia’s unconventional hydrocarbon resource potential. In consultation with the United States Geological Survey (USGS), a nationally consistent assessment methodology is being developed to derive unconventional hydrocarbon resource estimates of Australia’s prospective onshore basins that conform to internationally accepted standards.

Figure 1. Major sedimentary basins with CSG potential in Australia. Note that shading indicates entire extent of basins and does not delineate actual CSG plays within the basins.
These assessments aim to provide industry, government, research and public stakeholders with an objective insight into Australia’s unconventional hydrocarbon resource potential, beginning with the Georgina Basin.

Georgina Basin

Geological setting

The Georgina Basin is a Neoproterozoic to Lower Devonian sedimentary basin covering 325,000 km² of western Queensland and the Northern Territory. It is a northwest–southeast-trending extensional basin, with prospective conventional and unconventional hydrocarbon targets within Cambrian and Ordovician carbonate and siliciclastic rock units. The unconventional gas and oil potential of the basin has led to considerable recent exploration interest, although the basin has been relatively underexplored in the past (Smith et al. 2007, Carr et al. 2012).

The basin is bounded by Proterozoic rocks of the Mount Isa Province, South Nicholson Basin and Lawn Hill Platform to the north, the Tennant Region to the west and Arunta Region to the south (Southgate and Shergold 1991). It is continuous with the Daly and Wiso basins, to the northwest and southwest of the Tennant Region, respectively. Neoproterozoic extension in the Georgina Basin was followed by thermal subsidence, resulting in lower Cambrian sediments being deposited mainly in the south. It was not until the mid-Cambrian that marine conditions became widespread and deposition of marine facies occurred throughout the basin. Units deposited at this time included sandstone, conglomerate, shale and mudstone (Dunster et al. 2007).

Unconventional petroleum prospectivity: New work

As part of the prospectivity assessment of the basin, new geological studies have commenced in the Georgina Basin including: biostratigraphic age control, geochemical evaluation of potential source rocks and oil stains, and regional synthesis in a GIS framework.

This revised biostratigraphy and chronostratigraphic framework for the Georgina Basin provides a baseline for the first basin-wide assessment of its unconventional hydrocarbon potential. New biostratigraphic interpretations of the prospective southern, central and eastern regions of the basin have been revised to reflect the 2012 Geological Timescale (Gradstein et al. 2012), resulting in an updated chronostratigraphic framework for the basin. The revised biostratigraphic interpretations have implications for understanding the distribution of potential source rocks and petroleum systems (Figure 3). For example, the limestone unit in the southern part of the basin, generally regarded as the Thorntonia Limestone, has been found to be older than the type section for this unit, located in the Undilla Sub-basin, further east. As a result, the Thorntonia Limestone in the southern parts of the basin might need to be redefined (Smith et al. in press). Additionally, the basal ‘hot shale’

![Diagram](image1.png)

**Figure 2.** Major sedimentary basins with shale gas/oil potential in Australia. Note that shading indicates entire extent of basins and does not delineate actual shale gas/oil plays within the basins.
of the Arthur Creek Formation is diachronous across the Dulcie and Toko synclines, which has ramifications for hydrocarbon exploration (Smith et al in press).

Source rock studies have included screening using TOC and Rock-Eval pyrolysis methods, with Py-GC and kerogen kinetics being undertaken on selected immature samples to determine their ultimate potential and gas-oil ratios (GORs). Isotopic studies on oils and gases (both conventional and unconventional), collected during vertical and horizontal drilling and production testing, will expand the existing oil and gas families for selected onshore basins. To date, mud gases collected during shale gas and shale oil exploration drilling in 2012 have been analysed for their carbon isotopic compositions and further isotopic studies are planned on the hydrocarbon and inorganic gas components. Geoscience Australia has built up a library of the biomarker and isotopic signatures of Australia’s oils for the onshore basins, and oil family associations will be re-interpreted when supplemented by the results from recently sampled oil stains from the Northern Territory and Queensland.

In the Dulcie and Toko synclines, many mid-Cambrian petroleum systems are known from previous work. The oldest is the Thorntonia(!) Petroleum System, whereas the youngest is the Hagen(!) petroleum system (Ambrose et al 2001, Boreham and Ambrose 2007, Draper 2007). The Thorntonia(!) and Arthur Creek(!) Petroleum systems comprise hydrocarbons sourced and reservoired within the Thorntonia Limestone and Arthur Creek Formation, respectively, and generated by a Type II marine kerogen. The lower Arthur Creek Formation has high organic carbon contents associated with the ‘hot shale’, and it is this unit that is the focus of both shale gas and shale oil exploration. Oil stains recovered from the Hagan Member of the Chabalowe Formation, such as those in Randall-1, originate from source rocks deposited in a more saline environment. All Georgina petroleum systems are represented from shows data in both the Dulcie and Toko synclines, though the extent of the maturity of these systems across the basin needs further work.

Geoscience Australia is remapping the ‘hot shale’ and lower and upper Arthur Creek formations in order to calculate net to gross thickness for the assessment units. These data will be combined with geochemical data to produce a total petroleum systems model and refine the effective sources for shale gas and shale oil plays.

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A considerable area of the Northern Territory is underlain by flood basalts of the late early Cambrian Kalkarindji Suite. These basalts have a strong magnetic response that can be targeted using magnetic depth estimate techniques. To serve as a preliminary guide to the depth to the basalts in any area of interest, a set of magnetic depth profiles has been provided on the NTGS Geophysical Image Web Server (GIWS). Each depth profile consists of a set of smoothed spikes along a depth scale from 0 to 1000 m, where the size of the spike indicates the relative probability of a magnetic layer at that depth (Figure 1).

Each profile was derived using a version of a procedure usually ascribed to Spector and Grant (1970) along the power spectrum in the surrounding 20 x 20 km magnetic grid. Conventionally, each power spectrum would be examined and a single slope would be selected. However, the 15 000 profiles were of necessity, automatically derived through taking the slopes along the entire power spectrum. Inevitably, false spikes were created in the process. Although a major magnetic layer could be traced from one profile to the next profile, 20 km away, minor depth signals that possibly indicated a sought-after second layer were not sufficiently consistent to enable its resolution.

In order to suppress random spurious spikes, the process was repeated every 5 km. This spacing is sufficiently close to enable the spikes to be converted into a colour-scaled image of depths along a traverse across the NT. In this representation, the random signals are suppressed and a signal that repeats over four or more profiles can be seen to

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Figure 1. Spector Grant Depth Profile showing the relative probability that a magnetic layer is present at depths of up to 1000 m below the surface.
be real. **Figure 2** shows the location of two traverses that are discussed in greater detail below.

**Figure 3** shows depth traverse 1, located near the Western Australian border. The hot colours represent increased probability of a magnetic layer and the figure clearly shows continuous basalt at a depth of 200 to 250 m below surface, extending for more than 100 km. A borehole in the vicinity of the traverse intersects several hundred metres of basaltic material from near the surface, so what is being imaged is a more magnetic layer near the bottom of the basalt. This is to be expected, as the earliest basalt has flowed across a palaeotopographic surface, so its infill provides distinct signals in an ensemble of lumps that conforms to the original Spector Grant hypothesis.

The same figure shows an apparent body continuing near the surface. However, this is spurious and arises from noise in the low-power part of the power spectrum. In subsequent work, this distracting event has been suppressed and this is demonstrated in the presentation at AGES 2013 (Clifton 2013).

In the course of calibrating this process, progress was made towards tightening the range of depths for each event, making it a sharper signal on the image and resulting in a clearer interpretation. Because this involves an extension of the original theory of Spector and Grant (1970), the implications have yet to be fully explored. However, one significant and useful result is that the effect of different line spacing of the surveys can be predicted and removed. Because the extension of the theory refers to a layer of dipoles, rather than an ensemble of prisms as used by Spector and Grant in their original paper (ibid), the method no longer has to refer to a magnetic body, but more generally to a layer of magnetic objects. This has resulted in the technique being applied to identify ironstones in the Tennant Creek goldfield (**Figure 4**). The hot colours outline a feature that can be traced to the southeast of the goldfield and is interpreted to represent the depth and extent of these ironstones.

**References**


Geophysical targeting of potentially uraniferous stratigraphic successions under cover, northern Ngalia Basin, NT

Paul J Dunbar¹ and Bruce L Craven²

Introduction

Uranium mineralisation within the Ngalia Basin was first discovered in the early 1970s. Regionally, all bedrock uranium mineralisation occurs within the lower stratigraphic units of the Mount Eclipse Sandstone, with the most significant occurrences at Bigrlyi, Walbiri and Minerva. Although the individual deposits and all regional prospects evaluated to date have significant differences in their local geology, one aspect common to all uranium occurrences is that the mineralisation is hosted by reduced rocks within an overall oxidised stratigraphic sequence. Locating and accurately mapping the host reduced package, especially under cover, is considered to be the key to the discovery of new uranium deposits in the northern Ngalia Basin. Although the geological features that control the prospective reduced horizons are not a part of this report, it is acknowledged that there are multiple factors that control the distribution and formation of the reduced horizons at the three known deposits.

The regional geology of the Ngalia Basin has been described previously by Ivanac and Spark (1976), Wells and Moss (1983), Fidler et al (1990) and Young et al (1996). The basin architecture and uranium mineralisation of the Bigrlyi deposits were a significant component of the JSU (Joint Survey Uranium) Ngalia Basin Uranium Mineral System research project completed in 2011 (Schmid et al 2011).

Bigrlyi uranium deposit geology

The Bigrlyi deposits have been extensively studied since their discovery by Central Pacific Minerals (CPM) in 1973. Individual studies include work compiled in Ivanac and Spark (1976), Fidler et al (1990), Ashley (2009), Muhling (2010) and Schmid (2011). An informal stratigraphic sequence was developed by CPM for the Bigrlyi area with an overall upward-fining succession. Within this sequence, one horizon (Unit C) was identified as reduced sandstone underlain by oxidised sandstones (Unit D) and overlain by fine-grained sandstone, siltstone and shale (Unit B). The historical subdivision of Unit C and Unit D is now interpreted as being a change in the oxidation state that does not have any relationship to the original deposition. Therefore, Unit C and Unit D are now considered to be the same stratigraphic unit with the upper part usually reduced and the lower section oxidised (Muhling 2010). The difference between the two parts appears to be due to early haematite alteration of the lower sediments prior to cementation.

The reduced horizon was interpreted by Fidler et al (1990) as containing carbonaceous material and pyrite. Petrographic work on the Bigrlyi deposits by Ashley (2009), Muhling (2010) and Schmid (2011) has identified pyrite in variable concentrations within the reduced horizon. Only one thin section from these three studies definitively identified carbonaceous material; however, that was identified as being remnant hydrocarbons and not plant detritus or graphitic material. Chemical analysis of various samples has confirmed the lack of carbonaceous material in the reduced horizon. Samples submitted as a part of a metallurgical testing program were analysed for both organic and inorganic carbon, with less than 2.5% of the samples returning organic carbon above background (5x analytical detection limit of 0.02%); the maximum organic carbon content recorded from over 240 samples was 0.46%.

Another recently identified aspect of the Bigrlyi deposit is the extensive presence of carbonate cement adjacent to the reduced horizon hosting the mineralisation. The early carbonate cement (dominated by calcite) was interpreted by Schmid et al (2011) to postdate mineralisation. The carbonate cement occurs both stratigraphically above and below the reduced horizon with the cement in the underlying rocks usually being more pervasive. Recent re-interpretation of hyperspectral logs obtained during the JSU Ngalia Basin uranium mineral system study has identified that carbonate cement is present in most of the drillholes that were re-interpreted (Pontual 2012). Calcite is often the dominant spectral response stratigraphically below the mineralisation.

Recent geophysical probing of a series of drillholes at Bigrlyi confirmed that the zones of carbonate cement are commonly moderately to highly resistive (Wilde 2012).

Geophysical techniques

Successful application of geophysical techniques for targeting specific mineral deposits is reliant on its ability to map both the geological characteristics and orientation expected.

Ground and detailed airborne radiometric surveys have been successfully used to discover uranium mineralisation in areas of reasonable outcrop in both the Ngalia Basin and elsewhere. Direct targeting of uranium mineralisation under even thin cover is not possible using radiometric techniques because of the rapid attenuation of the radiation. However, several geophysical methods, including electromagnetic surveys (EM) and induced polarisation (IP) may allow the identification of prospective strata.

Importantly, both EM and IP techniques have advantages when targeting certain geological features expected in a specific mineral system, where subtle variations in the survey methodology can have a significant impact on the effectiveness of the survey.

1. EM surveys are a viable exploration tool when a geological body or unit is conductive and the orientation

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of the body is such that there is sufficient coupling between the transmitting loop and the conductive body. A good example of the use of EM within the Ngalia Basin has been the successful mapping of various Cenozoic palaeochannels, as detailed in Moloney (2011). In this case, the palaeochannels were accurately mapped using the TEMPEST airborne EM system, with the conductor being either lignite (intersected in some drillholes) or saline groundwater. The uranium mineralisation was interpreted as being hosted in the basal sediments of these channels. The use of EM to target bedrock uranium mineralisation or potentially uraniferous stratigraphy in the lower Mount Eclipse Sandstone is not viable due to the absence of any sufficiently conductive units within the sequence. A trial Airborne EM survey was flown at Bigrlyi in 2009. It failed to identify any conductive units that could correlate with geologically observed features in the stratigraphic sequence.

2. The IP method was recognised in the early 1920s and developed in the 1950s as a tool for identifying and mapping disseminated sulfide mineral systems, particularly porphyry copper deposits. Ashley (2009), Muhling (2010), Schmid (2011) and recent re-logging by the Bigrlyi Joint Venture identified small amounts (1–2%) of disseminated pyrite in the reduced horizon. Based on these observations, a trial IP survey was designed and conducted over several of the known zones of mineralisation in mid–late 2012. The aim of this survey was not to directly detect uranium mineralisation, but to map prospective reduced and potentially uraniferous host rocks under cover.

Southern Geoscience Consultants were approached to assist in designing a specific, cost-effective survey configuration and to process and interpret the results. The IP survey was conducted by Zonge Engineering, using a detailed gradient array configuration. It commenced in late 2012 and targeted the reduced horizon at Bigrlyi (Anomaly 4 and Anomaly 15) and elsewhere in the region. The concept of the survey was to map the extensions of the reduced stratigraphic succession (and structure) under cover, much like aeromagnetic surveys are used to map the geology and structure in covered and complex terranes.

The time domain gradient array IP-Resistivity trial collected data at 25 m intervals on 50 m spaced lines (50 m receiver dipole, 2 km current dipole) over a series of 600 x 600 m blocks. Data from this array configuration provides limited depth analysis and discrimination; however, it enables rapid data collection and mapping of each block. These data were quality controlled and processed, providing images and contours of the chargeability and apparent resistivity.

The initial IP trial area at Anomaly 4 is shown in Figure 1 with the detailed CPM map overlain on detailed photography. Figure 2 shows the outline of the CPM map and recently acquired, detailed ground radiometric data. Images of the processed gradient array IP data are included as Figure 3 (chargeability) and Figure 4 (apparent resistivity).

These images clearly show that the elongate, elevated IP high delineates the known prospective horizon (delineated by geological mapping and radiometrics), but it also maps extensions of the reduced horizon under cover. The apparent resistivity high also correlates reasonably well with the zone of more intense carbonate cement observed in the oxidised unit stratigraphically below the reduced horizon.

The measured IP within the Anomaly 4 survey area results in a peak response of chargeability of 5.8 mV/V with the overall background generally being around 1 mV/V. The observed apparent resistivity peaks at about 300 ohm-

![Figure 1](image1.png)  
**Figure 1.** Detailed CPM 1:2000-scale geological mapping overlain on digital aerial photograph showing the cover between mapped outcrops.
meters (Ωm) with the background to the north of the reduced horizon (Unit B) being around 50 Ωm, whereas the response within the reduced horizon was between 100 and 150 Ωm.

When interpreting these IP data, it is critical to compare the geophysical response with the interpreted geology, as each geological package will have a different background response. The low-magnitude but consistent and coherent IP response is interpreted as mapping pyrite (with possible marcasite) within the prospective reduced horizon. The unconfirmed presence of carbonaceous material would also result in an IP response. The apparent resistivity shows a general peak immediately to the north of the IP feature; this is interpreted as a response to the carbonate cement observed stratigraphically below the mineralisation.

**Conclusions**

Uranium mineralisation observed at Bigryli (and other prospects within the Ngalia Basin) is associated with reduced sediments. The delineation of these prospective horizons is

![Figure 2. CPM mapping overlain on Ground Radiometric Survey over the Trial IP area.](image1)

![Figure 3. IP Chargeability image overlain by CPM map. Image shows extension of the reduced horizon under cover.](image2)
relatively easy in areas of good exposure via routine mapping and radiometrics. However, cost-effective mapping and testing of the reduced sediments under cover is the key to the discovery of further significant mineralisation within the basin.

Gradient array IP has been trialled over known uranium mineralisation at Bigrlyi and has confirmed that the geological features associated with the mineralisation can be successfully mapped below thin cover. Based on the initial results, the reconnaissance IP-resistivity surveys are providing an efficient means of optimising routine exploration drilling of the prospective horizons. Further work is required to evaluate whether other mineral systems, also associated with reduced stratigraphy, can be successfully mapped and targeted using the gradient array IP method.

Acknowledgements

The contribution of the geological and field staff from Energy Metals along with the work of Zonge Engineering and Michael Sykes of Southern Geoscience Consultants has greatly expanded the geological and geophysical understanding of the Bigrlyi deposit. The management of Energy Metals is thanked for allowing this work to be released. The work of reviewing this abstract by Lindsay Dudfield is greatly appreciated.

References

COBRA – Amadeus Basin project: Introduction and first results

Susanne Schmid

The Central Oz Basins Resource Assessment (COBRA) initiative is a collaboration between CSIRO, the Northern Territory Geological Survey, and industry partners Central Petroleum Ltd and Globe Mineral Resources Investment P/L. The project aims are to assess the mineral (U, Cu, Au, Pb, Zn and Mn) and unconventional hydrocarbon potential of central Australian sedimentary basins, by applying and bringing together new technology and systems thinking from hydrocarbon and minerals research. The expected outcomes will be geochemical vectors to exploration, linking the understanding of the depositional environment with hydrocarbon and mineral systems, and enhancing the potential for new discoveries.

The research project consists of basin-scale and deposit-scale modules running over 3 years. The basin-scale study focuses on the regional architecture of the Amadeus Basin and its potential for minerals and hydrocarbons. This basin has received some attention from hydrocarbon explorers over the last 50 years, but its mineral prospectivity is poorly constrained. The deposit-scale study (currently not exercised) will be focusing on requests from partners and could be located either in the Amadeus Basin, or in adjacent basins with a geological context (eg equivalent stratigraphic unit) that can be correlated to the Amadeus Basin.

The main aims of this project are to: (1) find the pathways between source and sink of minerals and demonstrate the tools that can be used to map these systems, so as to open up new areas for exploration; and (2) generate 3D datasets of prospective source and host rock units that can lead to a better understanding of the basin architecture.

The first results of the work program, which has reached the end of its first year, are: (1) a compilation of all existing data; (2) depth inversion and modelling of the 2012 NTGS East Amadeus gravity survey; (3) early stages of geochemical characterisation of the stratigraphy; (4) integration of water bore data (Figure 1) into all geological and geophysical models; and (5) conversion of outcrop geology into 3D.

Figure 1. Depth to basement map of southern Amadeus Basin margin, generated from water bore data only (preliminary). Red colours represent shallow sediment depths, green colours represent increasing sediment thickness. Background is Landsat bands 742 image.

More revealing – new images of the Amadeus Basin from closely spaced gravity measurements

Clive A Foss1,2, James R Austin1 and Susanne Schmid3

Regional geophysical surveys provide valuable information about geological structure and basement depth. Gravity surveys, in particular, can be used to locate the positions of steeply dipping subsurface interfaces between rocks of different density. Quantitative interpretation of gravity data, in the form of modelling, is able to test concepts of geological structure against the constraints of the measured gravity values. Both the resolution of gravity map images and the discrimination of resulting models depend on the quality and distribution of the gravity measurements. Until recently, the gravity coverage of the Amadeus Basin was mostly only by the gravity stations of the original national

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survey, with measurements at nominal 11 km spacing. A series of regional gravity surveys by NTGS, most recently the Eastern Amadeus Gravity Survey, have reduced the gravity station spacing across most of the basin to a 4 km spacing (an almost 8 fold increase from one station per 121 km² to one station per 16 km²). There are also areas of higher density infill at 2 km and 1 km station spacing, together with some detailed gravity traverses, mostly acquired along seismic lines and available roads.

The new gravity data, together with high-quality seismic profiles acquired by Central Petroleum Ltd, and some recent drilling, provide new information with which to upgrade the understanding of the structure and evolution of the Amadeus Basin. The COBRA (Central Oz Basins Resource Assessment) project is a collaboration between CSIRO, NTGS and industry sponsors to create a new, integrated model of the structure, stratigraphic succession, sedimentology and fluid history of the basin. This presentation reports on the main geophysical component of that project, which is to develop a model of the basin structure, based on interpretation of regional gravity and magnetic data, with the benefits of (sparse) seismic and borehole control.

The new gravity data

Figure 1 shows the pre-2008 gravity stations across the Amadeus Basin. The coverage incorporated 26 556 stations at an 11 km spacing, together with detailed traverses along seismic lines and some tracks. Figure 2 shows the present coverage, which includes a further 26 939 stations. The most recent addition to this coverage is the Eastern Amadeus Gravity Survey, completed by NTGS in September 2012, as part of the Bringing Forward Discovery Initiative. This survey involved the acquisition of approximately 7560 helicopter-supported ground gravity stations, mostly at a station spacing of 4 km, but with infill of local areas at 2 km and 1 km spacing, with industry collaboration. The increased information content resulting from the addition of this new data is most evident in enhanced imaging of the gravity field, which benefits considerably from constraint of the true gradients at wavelengths down to 8 km, rather than their interpolation between the previous gravity stations at wavelengths down to only 22 km. These shorter wavelength variations are primarily sourced in the top 4 km of the subsurface, improving the mapping of density variations associated with the basement interface, and any steeply dipping intra-basin density contrasts (such as clastic rocks/salt contacts generated by salt tectonics). The small infill areas with station spacings of 2 km and 1 km clearly reveal that further improvements in mapping the gravity field would result from further infill in the 4 km spaced regions (and particularly in the remaining western area of sparse coverage).

COBRA gravity and magnetic modelling

The two principal regional geophysical coverages of gravity and magnetic data provide almost independent information. The gravity data is influenced by the distribution of density, which is a bulk, whole-rock property. Over the large study area, the various causes of gravity variation include regional changes in crustal thickness and composition, lithology variation in the shallow crust, variation in depth to basement beneath the Amadeus Basin (one of the principal interpretation objectives), and lateral differences in density of the basin infill (particularly between clastic rocks and salt). The magnetic data however is only influenced by the ferromagnetic mineral content of the rocks, which even for strongly magnetised rocks, generally constitutes only one or two percent of the rock. In many areas, there is little or no contrast in magnetisation between basement
rocks and basin sedimentary rocks, so that this interface is only intermittently imaged by the magnetic data. Most of the magnetic field variation over and around the Amadeus Basin is from sharp intra-basement contrasts between weakly magnetised units such as granitoids, and strongly magnetised units such as amphibolites, gabbros and basalts. Over the shallow basin margins and surrounding basement, the magnetic field data images local basement structures and magnetisation contrasts, but over the deeper parts of the basin, only the largest and most strongly magnetised basement units give rise to detectable variations in the magnetic field. In these magnetically quiet areas of deep basin, weak magnetisation contrasts within the basin sedimentary rocks can also be recognised. This magnetic signal arises from discrete stratigraphic units in the shallow subsurface, and in some areas, maps the disruption of those units by salt tectonics. Depths to basement beneath the basin can be determined from inversion of profiles across the suitable basement-sourced magnetic anomalies, but only at the locations of those anomalies, leaving considerable interpolation to produce a useful mapping of the basement surface. Basement-related variations in the gravity field are continuous, but are not in themselves suitable for direct inversion to map a basement surface, because the density contrast between the basement and basin infill is uncertain, and because crustal thickness, basement lithology and intra-basin density contrasts all also contribute to the measured gravity variations, and cannot be separated without independent constraints. The discrete magnetic depth estimates provide some constraints, with the resulting calibrated model then consistent with both the measured gravity and magnetic fields. There are presently insufficient independent constraints to build a definitive model of the Amadeus Basin from gravity modelling. One of the principal uncertainties is in constraining gravity lows due to thick sections of salt from those due to basement topography. In view of these limitations, COBRA is constructing a ‘live’ gravity model, which will become available for editing as new gravity data, seismic or borehole constraints become available, or to test new structural interpretation concepts.

Figure 2. Present gravity station coverage across the Amadeus Basin within the Northern Territory.

Alligator Rivers uranium: Facts and fiction

Andrew Browne1

Exploration for and discovery of ‘unconformity-related’ uranium deposits in the Alligator Rivers Uranium Province (ARUP) since the 1960s has been hampered by poor outcrop, variably thick surface cover, deep weathering, political interference, and a regrettable dependence on a model-driven philosophy unrelated to observable facts.

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Other known types of uranium occurrences in the ARUP include: (1) very localised uranium enrichment associated with Mesoproterozoic tuffaceous units; (2) minor vein enrichments in late Mesoproterozoic acid and mafic intrusive rocks. The occurrence of the latter is quite important, as it represents the fairly wide availability of U-rich fluids, deposited in localised host structures in association with late tectonic events.

The characteristics of Neoarchaean–Palaeoproterozoic basement rocks (lithologies, geomechanical properties),
in terms of the reaction of the various units to tectonic and chemical forces, are of primary importance. Hence a knowledge and understanding of the nature and distribution of basement lithologies is critical.

Observable facts include:

- **Pre-Mesoproterozoic metamorphic basement** comprises at least four separate upward-fining metasedimentary sequences on Neoarchaean cores (Carson et al. 2011, Hollis and Glass 2012).
- **Known unconformity-related U deposits** are concentrated in two of those sequences.
- The proportion of carbonaceous material in the ARUP is totally insufficient to act as a reductant for the uranium deposition. The source of at least some graphic material in known deposits is equivocal, possibly involving methane chemistry from mineralising fluids.
- The relative proportion of Fe- and Mg-rich chloritic material in known ARUP deposits is such that a significant Eh/pH event involving these precursors alone may be sufficient to explain uranium precipitation at the general grades observed.
- There are at least five separate groups of ages of uranium mineralisation between 1845 Ma and 420 Ma (Table 1), indicating that the earliest mineralisation is associated with the regional Nimbuwah Event, and four other groupings are associated with North Australian Craton tectonic events, all demonstrating local chemical and structural remobilisation and reactivation at U deposits.
- The remobilisations appear to have concentrated uranium, especially where reactivations have further prepared larger breccia zones.
- Known structures hosting U mineralisation comprise initial listric thrusters associated with the Nimbuwah Event that have been modified by subsequent tectonic reactivation. At least some prominent mineralised reactivated structures appear to be oriented normal to the local stratigraphic succession.
- The reaction of host units to the tectonic events and to the chemistry of fluids carrying uranium and other elements is varied, with carbonate-rich zones being preferential depositories. These are more susceptible to structural reactivation due to their competency contrast with surrounding units, as well as to reaction with acid fluids.
- Gold and copper mineralisation at the Ranger and Jabiluka deposits is related to much later events, where vein systems carrying Au and Cu minerals cross-cut at least two stages of earlier U mineralisation. There is no statistical correlation between U content and either Au or Cu, other than within narrow veins.
- Detailed lithgeochemical studies at Ranger indicate that the mineralising fluid events culminated in local depletion of LREE, Ba, and K, and local enrichment of HREE and Mg (Cleverley et al. 2009, Potma et al. 2012). However, a genuine identifiable vectoring alteration geochemical halo has yet to be identified.
- Early basement structures do not penetrate the Mesoproterozoic Kombolgie Subgroup.

### Table 1. Alligator Rivers Uranium Province stratigraphy, tectonics, geochronology and uranium mineralisation.

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>Sequence or unit (Ma)</th>
<th>U mineralisation age (Ma)</th>
<th>Regional tectonics (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–570</td>
<td>Quaternary; Cenozoic; Cretaceous</td>
<td>420–460 ca 520</td>
<td>Alice Springs Orogeny (300–450) Petermann Orogeny (530–580)</td>
</tr>
<tr>
<td>?1688</td>
<td>Oenpelli Dolerite</td>
<td>1550–1650</td>
<td>Isan Orogeny (1500–1620)</td>
</tr>
<tr>
<td>1820–1870</td>
<td>Felsic intrusive rocks: Naborlek Granite (1818), Cullen and Jim Jim granites (1820–1835), Tin Camp Granite (1846), Ranger pegmatite (1847), Nimbawuh granitoids (1860–1870)</td>
<td></td>
<td>Nimbawuh Event (1855–1865)</td>
</tr>
<tr>
<td>1870–2500</td>
<td>Caramal, Birraduk, and Namarrkon dolerites, intrusive into: Nourlangie Schist and un-named units east of East Alligator River</td>
<td></td>
<td>Sleaford Orogeny (2420–2440)</td>
</tr>
<tr>
<td>Cailhill Fin</td>
<td>Un-named units at Cannon Hill</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arrarrar Gneiss; Njibinjibinj Gneiss (2640–2670)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• At least one generation of later structures in the Kombolgie Subgroup has followed pre-existing basement weakness zones, demonstrating reactivation. The orientation of mineralised structures in the basement sequences at Jabiluka is quite different to mapped faults and joints of the Kombolgie Subgroup.

• Mafic intrusive rocks of the ARUP are divisible into the ca 1700 Ma Oenpelli Dolerite and a 1300–1400 Ma event (Goldberg 2010). Many outcrops of doleritic material in the ARUP have been ascribed incorrectly to the Oenpelli Dolerite, and better distinguishing features are needed (most likely requiring geochemistry and detailed petrography).

• Uranium is found occupying narrow veinlets in the skin of late dolerites (eg South Horn, Orion), demonstrating a widespread, late U fluid availability and mobility.

Several fictions are still applied to uranium exploration concepts in the ARUP:

• The most common fiction is that all unconformity-related uranium deposits share common major characteristics, and hence exploration programs suitable for one basin should be applicable to the entire class. In fact, the observational differences between the structural, geochronological, and stratigraphic characteristics of the Athabasca, Thelon, and Alligator Rivers Uranium Provinces are profound, and are more far more important than the apparent similarities. The other fictions below all relate to this dominant misconception.

• Uranium precipitation requires oxidising fluids from within the Kombolgie Subgroup to move down fault structures. In fact, there is no evidence for early or initial mineralisation/alteration-related oxidising fluids in the Kombolgie Subgroup, and none for descending movement.

• Uranium occurs within the Kombolgie Subgroup. In fact, all occurrences noted to date (Jabiluka, Angularli, Arrari) occur within chloritised structures enclosed in the Kombolgie Subgroup, but actually remobilised up from basement rocks within obvious late structures penetrating the basement.

• There is a pre-Kombolgie Subgroup weathering surface. In fact, the mapping of hundreds of kilometres of sub-Kombolgie unconformity, plus the logging of tens of drillholes through the unconformity has produced no conclusive evidence for such a feature, and considerable evidence for its absence.

• Carbonaceous or graphitic material is essential for localisation of uranium. In fact, the proportion of carbon in the ARUP is small, except very locally; it is insufficient to account for U precipitation and is extremely difficult to detect using electrical geophysical systems in the ARUP, due to conductive overburden and low concentration.

Observations made at the large number of known unconformity-related uranium mines and prospects in the ARUP must share a logical and mutually satisfactory explanation. The known deposits exhibit at least two major common features: preferential location in stratigraphic units with demonstrable competency contrast, possibly where chemical dissolution of brecciated zones has enhanced that contrast; and structural dislocation normal to the dominant stratigraphy. Further work is required, especially on geochronology and mapping, to better understand these important deposits.

Acknowledgements

Numerous geoscientists from industry, government, and academia have contributed to my views since 1969, and continue to do so. Their observations are gratefully acknowledged, but without penalty, as all interpretations are entirely my own. The continued encouragement of the management of Alligator Energy Ltd is gratefully acknowledged.

References


Carbonate platforms: here today, skarn tomorrow? Developments in the understanding of the mineralisation potential at Thundelarra's Allamber Project

Costica Vieru1, Harry Mees2 and Tony Lofthouse1

Thundelarra Exploration Ltd (Thundelarra)’s Allamber copper-uranium project is located to the northeast of Pine Creek in the Palaeoproterozoic Pine Creek Orogen (PCO). Over the past few decades, base metals exploration in the Allamber project area and in the Mary River area to the northwest has been relatively superficial and based largely on surface geochemistry. Drill testing of a number of resultant uranium and copper targets has not elucidated the style and economic potential of these mineral occurrences. Past exploration within the area was concentrated on the known uranium occurrences at the Cleo and Twin Dam prospects, discovered by Total Mining Australia Pty Ltd in 1983. Uranium was also the main target elsewhere in the project area, particularly along the contact between the Allamber Springs/Frances Creek granites and country rocks. Aztec Mining Company Ltd had targeted the same contact in the early 1990s for its base metals potential using the Woodcutter’s mineralisation model and their drilling encountered sporadic low-grade copper intersections. In 2011, Thundelarra hit two significant copper intercepts at the Hatrixt prospect (19 m at 1.94% Cu and 17 m at 1.09% Cu: ASX Announcement 29 September 2011), immediately after the company shifted its exploration focus from uranium to base metals in the wake of the Fukushima earthquake and tsunami.

Thundelarra’s recent work on the western contact of the Allamber Springs/Frances Creek granites in the PCO has identified the presence of an extensive carbonate platform and moderately high potential for copper, tin, tungsten, bismuth, gold, lead and zinc mineralisation, related to the highly fractionated granitoids and their associated metasomatic phases (ASX Announcements, 4 October and 29 November 2012). It is now becoming clear that polymetallic mineralisation is closely related to these granitic intrusions and the mineralisation styles identified to date include: sulfide-quartz lode systems within granite; and calc-silicate-associated type within the metasedimentary rocks of the contact metamorphic aureole of the plutons. Carbonate-replacement style deposits can also occur at a considerable distance away from the intrusive sources and encouraging signs of this type of mineralisation have been recognised within several areas. Petrographic and mineragraphic studies have confirmed that potassic alteration, clay-sericite development on plagioclase, and chloritisation of biotite and amphibole are common features within the more fractionated alkaline granitic intrusions.

Drilling completed in the last quarter of calendar year 2012 delivered further significant uranium intersections at the Clift South prospect, including 23 m at 1304 ppm (2.9 lb/t) U3O8 and 19 m at 821 ppm (1.8 lb/t) U3O8. The potential for graphite was also established along the Cullen Supersuite metamorphic contact within carbonaceous shale of the Masson Formation (ASX Announcements, 10 October and 12 December 2012).

Thundelarra’s exploration programs in 2013 will continue to focus on developing our understanding of the complex geological setting at Allamber and on targeting areas of potential mineralisation of varying styles.

Rare earth reflectance spectroscopy: Some NT examples and exploration implications

Belinda R Smith1 and Jon F Huntington2

Initial HyLogging of drill core containing rare earth elements (REE) housed in the NTGS Core Facility has highlighted that the spectral responses of REEs are distinctive. Many light and heavy REE reflectance spectra show sharp absorption features at diagnostic wavelengths (notably in the Visible to Near Infrared [VNIR]). Additional non-REE spectroscopic features have provided information on host lithological composition and settings.

To provide further spectral characterisation of REEs, samples from three different rare earth deposits from across the Northern Territory were scanned using the HyLogger 3-7 instrument. These deposits include the hydrothermal stockwork, vein-style, Nolans Bore REE-phosphate-uranium deposit in the Arunta Region, the alluvial-style Charley Creek REE deposit in central Australia and the HREE Stromberg prospect in the Birrindudu Basin (Scrimgeour 2013). Since scanning of drill core (NBDH037) from the Nolans Bore deposit in 2010 [with initial VNIR and Shortwave Infrared (SWIR) results reported in AGES 2011 (Smith 2011)], work has concentrated on:

a. furthering our understanding of the spectral characteristics of REE minerals by rescanning Nolans Bore core to obtain Thermal Infrared (TIR) anhydrous silicate spectra (notably to characterise apatite)

b. increasing our understanding of the basic spectroscopic characteristics of RE oxides and RE-bearing minerals, using examples from the Northern Territory

c. investigating the quantitative relationships between REE content and absorption features, using data from Nolans Bore and Charley Creek

d. investigating the application of reflectance spectroscopy for identifying various REE minerals.

As part of the collaboration between CSIRO, GSWA and NTGS, the spectral characteristics of RE oxide

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new insights on the geology of the Nolan’s bore rare earths deposit

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The Nolan’s Bore REE-P-U deposit is located 135 km northwest of Alice Springs in the Northern Territory, and is hosted by metamorphosed Palaeoproterozoic igneous and sedimentary rocks in the Aileron Province of the Arunta

Region. Extensive recent infill resource definition and exploration drilling has significantly improved the geological understanding of this deposit. Nolan’s Bore now contains JORC-compliant Mineral Resources totalling 47 Mt at 2.6% REO, 11% P2O5 and 0.02% U3O8 using a 1.0% REO cut-off grade (Arafura Resources Ltd, ASX Announcement, 8 June 2012) and JORC-compliant Ore Reserves totalling 24 Mt at 2.8% REO, 12% P2O5 and 0.02% U3O8 (Arafura

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 standards were measured using a variety of spectrometers, to start compiling a table of diagnostic wavelength features (Figure 1). From this work, it was noted that most RE oxides have characteristic VNIR-SWIR absorption features that may assist in their identification.

Neodymium is the most spectrally-active REE at Nolan’s Bore and TIR HyLogging effectively maps the apatite host in NBDH037. An initial review of relationships between assays and the depths of spectral absorption features (particularly the 740 nm feature) indicates that these correlate rather well, although exact correlation is hampered by different sampling intervals (1 m assay intervals vs 18 mm spectrum intervals). At Charley Creek, alluvial REE-bearing RC chip samples also showed distinctive HyLogger Nd spectral responses.

At Stromberg, HyLogging of the drillcore showed that mineralisation is within very well crystalline kaolinite, with a sharp change in kaolinite crystallinity reflecting a change between anomalous REE content and background. Subtle absorptions at about 655 nm, 811 nm and 919 nm were noted and may reflect a mix of several rare earths (possibly dysprosium and erbium), although further work is needed to correlate spectral features with the presence of specific elements.

Recognising that various rare earth elements have distinct spectral characteristics has led to the identification of possible REEs in drill cores that have not been previously assayed for REEs. For example, samples of drill core3 from the Oonagalabi Cu ± Pb and Zn prospect (SLX001) have sharply defined REE-like spectra at 505 nm and 545 nm that are still to be identified, as these spectra are unlike any of our REE standards. A pronounced rounded feature at 960 nm appears to indicate anthophyllite, which has been confirmed by XRD as anthophyllite/gedrite. Industry core scanned through the HyLogger has also led to the identification of possible REE material in a vein from another NT prospect.

Reflectance spectroscopy is able to identify the presence of REEs in drill core that was not assayed for REEs at the time of drilling. The spectral responses are distinct and can be used as a guide in screening samples for REE assays and may identify REE occurrences (‘mining the core library’). Further work is continuing on validating the spectral response against other analytical techniques and further characterising the spectral response from pure REE oxides to those found in mixed REE minerals.

References


Figure 1. VNIR-SWIR reflectance spectra of REE oxide samples (>99.99% pure standards) in alphabetical order. Oxide samples were scanned using HyLogger 3-1 and many show the greatest spectral variation in the VNIR (380 – 1070 nm).

1 This drillhole was partly funded through the NT Government’s Geophysics and Drilling Collaborations Program.
Resources Ltd, ASX Announcement, 11 December 2012). The mineralisation at Nolans Bore is LREE-enriched and its Nd content is the highest proportion of any REE resource currently being advanced for development. The declaration of Ore Reserves and the production of REO products to required specifications lay the foundation for the commercial development of Nolans Bore.

Arafura Resources Ltd (Arafura) conducted a substantial RC and core drilling program across Nolans Bore in 2011, with a total of 27 761 m in 208 RC drillholes and 22 681 m of drill core, of which 56 holes were cored from surface and 126 holes were drilled as core extensions to RC drillholes. There is now more than 90 km of drilling in the Nolans Bore area with most of the deposit systematically drilled down to a nominal 250 m drilled depth on 40 m-spaced inclined (60°) holes along 40 m-spaced NW–SE sections. Some parts of the deposit have been systematically drilled on 20 m centres. To resolve and confirm emerging geological models, 25 inclined holes were cored from surface on six 100 m-spaced E–W sections during 2011. In addition to the systematic drilling, 20 geotechnical and metallurgical core holes were drilled in a number of directions and have greatly aided geological interpretations. The resource definition and exploration program was highly successful and met Arafura’s primary objective: to define Measured and Indicated Resources that could be converted to Ore Reserves capable of supporting a minimum 20 year mine life at a production rate of 20 000 t REO per annum.

The new geological model for Nolans Bore reveals that the geometry of the Mineral Resources is more complex than previously thought (Figure 1). The revised geological model shows that the mineralisation can be broadly divided into a North Zone (NZ), Central Zone (CZ) and Southeast Zone (SZ), with each zone containing about one-third of the defined Mineral Resources. The deposit remains open at depth, with deeper exploration drilling identifying resources at about 490 m drilled depth below the Central North Zone (CNZ). Exploration to the northeast of Nolans Bore has also identified new shallow resources, but these are yet to be fully explored. Like other isolated intervals of mineralisation, they have not been included in the identified Mineral Resources.

Structural measurements demonstrate that steeply dipping mineralised veins are dominant at Nolans Bore; steep northeast to northwest dips are most common, but all directions are represented. There is also a small subset of sub-horizontal veins. The higher drilling density has shown that the mineralisation at Nolans Bore occurs as a complex, three-dimensional vein system. This is contrary to previously published statements and largely a result of extensive core drilling outside the CNZ. The identified resources vary from continuous massive intervals of 4–7% REE mineralisation to lower-grade intervals, typically represented by a stockwork or cluster of veins, diluted by intervening unmineralised and variably altered country rock. High-grade (up to about 40% REE) secondary mineralisation is localised and represents only a small fraction of the identified Mineral Resources. The main mineralisation styles are massive fluorapatite, fluorapatite-allanite, fluorapatite-allanite-calcsilicate, plus kaolinitic- and clay-rich altered zones and equivalents...
that are dominated by secondary monazite and crandallite group minerals. Together these represent the dominant mineral phases at Nolans Bore, but in reality, numerous other minerals exist. Despite the extent of the deposit and the variety of minerals, the overall REE geochemistry is relatively uniform throughout the deposit. However, the secondary mineralisation does have a very different P/REE ratio compared to the other mineralisation types.

The mineralised veins are up to tens of metres in width and can be hundreds of metres in length. Observed mineralised vein margins range from sharp to irregular. Most vein margins commonly show adjacent calcsilicate alteration (wall rock replacement), which may be compositionally zoned (e.g. clinopyroxene to garnet). The calcsilicate alteration is variable; it is not always present, may be very narrow, and in some places, is extensively developed. There are variations in the calcsilicate mineral assemblages and these appear to be largely dependent on the host rock composition. The early-formed veins tend to be dominated by fine to very coarse fluorapatite infill containing fine-grained monazite and other REE mineral inclusions. These veins are sometimes locally overprinted by allanite-bearing veins. Weathering and oxidation complicates the mineralogy and textural features, and is strongly developed in the NZ and the northern part of the CZ.

The 2011 core drilling program better defined the nature and extent of the mineralisation and alteration at Nolans Bore and led to the recognition of the importance of some new mineralisation styles. Although fluorapatite-allanite mineralisation had been previously identified throughout Nolans Bore, the absence of drill core outside the CNZ meant that the nature and extent of the allanite-rich, fluorapatite-allanite mineralisation style observed in the CZ was not fully appreciated. This unusual style is best expressed and is most prominent in the CZ (Figure 2), but is also found in parts of the NZ. The newly recognised fluorapatite-allanite mineralisation style contains significant allanite, locally up to about 25%, occurring as prominent veins and is associated with distinct fluorapatite-allanite-amphibole breccias, typically flanked by extensive epidote-rich calcsilicate alteration. The abundance of allanite and the absence of associated calcite, the presence of hydroxyl-bearing minerals (amphibole, epidote and allanite) as breccia and vein infill, the presence of spalled and resorbed fluorapatite clasts, and extensive calcsilicate alteration haloes in the CZ contrasts with relationships typically observed in other mineralisation styles at Nolans Bore. For example the massive fluorapatite-rich, allanite-poor mineralisation style occurs throughout the deposit and is also found in parts of the CZ; however, the allanite is typically a trace mineral in this mineralisation style, and often associated with calcite.

The nature of the allanite-rich, fluorapatite-allanite-amphibole mineralisation style found in the CZ indicates that there was a significant change in the mineralising system. Early-formed apatite crystals are incorporated as euhedral, rounded, fractured or spalled fragments in a variable, matrix- to clast-supported breccia. Most importantly, fluorapatite clasts sometimes show apparent reaction textures on their margins, whereas other fluorapatite clasts

![Figure 2](image-url). Typical fluorapatite-allanite-amphibole breccia from NBDH1099 in CZ at Nolans Bore.
show corroded and resorbed textures. Rare examples of clinopyroxene-rich clasts are also found amongst the spalled clasts, implying that fragmented wallrocks might also be incorporated in this breccia. The relationships suggest that an initial fluorapatite-rich mineralised vein progressed to an allanite-rich vein system/breccia chamber, with associated amphibole infill and extensive epidote alteration. Fluid boiling is suggested as a plausible mechanism to explain this phenomenon. However, unlike the massive fluorapatite mineralisation, preliminary studies have shown that most of the fluorapatite clasts in the fluorapatite-allanite amphibole breccia contain allanite inclusions, rather than monazite inclusions as is common elsewhere.

The fluorapatite-rich rocks and their weathered and oxidised equivalents are the dominant mineralisation style throughout most of the deposit. The fluorapatite-rich mineralisation style typically contains REE-Th-U-bearing oxides, carbonates and phosphates. Mineralogical analysis has shown that the majority of the REE in the fluorapatite-rich style occurs within monazite; however, fluorapatite and claddilites are also significant REE-bearing phases. Allanite and associated allanitic epidote are the dominant REE phases in allanite-rich fluorapatite-rich mineralisation, with REE carbonates, monazite, claddilites and fluorapatite being less abundant.

The Nolans Bore deposit clearly postdates the high-grade ca 1590 Ma Chewings Event and relationships demonstrate that the granulite-facies metamorphosed igneous and sedimentary host rocks were locally reworked and retrogressed prior to the emplacement of the primary mineralisation and alteration system. U-Pb apatite dating has yielded a preliminary age of 1240 ± 15 Ma for the deposit. This age does not match any known events in the Arunta Region and caution should be exercised as attempts to date the deposit have proven difficult (Huston et al 2011). Huston et al (2011) also pointed out that isotopic signatures found in the mineralisation at Nolans Bore are reminiscent of an EM-1 source and, along with its distinct geochemical signature, favour a genetic link to carbonatite-derived hydrothermal fluids. The relationships expressed by the mineralised veins and the alteration system suggest that the deposit was formed at a relatively high-crustal level. This has important tectonic implications for the region, as the overprinting Alice Springs Orogeny (eg Raimondo et al 2012) indicates that Nolans Bore was at mid-crustal levels during that event, suggesting that the crust has bounced up and down several times.

Acknowledgements

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References


Reliable drill targeting from interpretation of magnetic field data

Clive A Foss

Effective exploration for subsurface mineralisation requires some form of remote sensing, which might involve surface geochemical sampling, or airborne or ground geophysical surveys, including for instance, gravity, magnetic or electromagnetic methods. To promote effective mineral exploration across the Northern Territory, NTGS has flown regional magnetic and radiometric surveys over most of the Territory, typically at line spacings of 400 to 200 m, and at ground clearances of 80 to 100 m. In many areas, this magnetic data provides a more complete and detailed imaging of geological structure than is available by geological mapping or other methods. Furthermore, based on the expected association of magnetite and pyrrhotite with some styles of mineralisation, anomalies in the magnetic data that are interpreted as expressions of mineralisation found in the mineralisation at Nolans Bore are reminiscent of an EM-1 source and, along with its distinct geochemical signature, favour a genetic link to carbonatite-derived hydrothermal fluids. The relationships expressed by the mineralised veins and the alteration system suggest that the deposit was formed at a relatively high-crustal level. This has important tectonic implications for the region, as the overprinting Alice Springs Orogeny (eg Raimondo et al 2012) indicates that Nolans Bore was at mid-crustal levels during that event, suggesting that the crust has bounced up and down several times.

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References


abstract considers these two factors separately, using some examples of Northern Territory magnetic anomalies. These problems are exacerbated for deeper sources, because errors in the horizontal or vertical position of a source body can generally be expressed as a percentage of its depth, and because the much greater cost of deep drilling makes such errors more expensive.

**Estimation of depth to a magnetic source**

Solving for the depth of a magnetic source from interpretation of magnetic field data is known as the ‘inverse’ problem (as opposed to the ‘forward’ problem of computing the magnetic field from a known source). The forward problem has only one correct solution, but the inverse problem is inherently non-unique. That is, there are an infinite number of possible solutions and it is not possible, from the magnetic data alone, to select the correct answer. One example of non-uniqueness is the inversion of magnetic field data due to a compact source which can be reasonably approximated by a sphere. Inversion can provide the depth to the centre of the sphere, but the magnetic expression of a small, strongly magnetised sphere is identical to that of a larger more weakly magnetised sphere. Therefore, it is not possible to reliably determine the depth to the top of such a source, only that it should be no deeper than the estimated depth to its centre.

Geophysical literature is full of methods to estimate depth to source from magnetic field data, many of impressive mathematical provenance, but none of sufficient reliability that they should be used as the basis for drilling an expensive deep hole. Rather, any drill target should be defined by careful inversion of the existing data. There are two common classes of inversion regularly applied to magnetic field data: smooth voxel inversions (for example UBC Mag3D) and parametric inversion (for example ModelVision). Smooth voxel inversions have an important role to play in 3D mapping of magnetisation, once depth to the top is known or well constrained. However, these inversions are not suitable for depth to source estimations. They have smoothness and depth weighting settings that determine the resulting estimated depth of the magnetisation. The only sensible question of the depth to a magnetic source must include provision of its postulated shape. Depth then becomes one of a set of parameters, and its value can be optimised by parametric inversion. The quality of the resulting depth estimate relies on the appropriateness of the shape assumption, but fortunately at greater depths, the details of shape irregularities become less significant. Consider a source postulated to be ‘tabular’ (shoe-box like). The prime parameters are its magnetisation, depth to the top, width, length, strike azimuth, plunge and depth extent. A well conducted inversion can find the best combination of those parameters to define the preferred source model (that which best fits the data). To evaluate the sensitivity of this process, and possibly provide a basis to decide on drilling beyond target depth if the body is not intersected, a suite of inversions can be run with depth held at some fixed offset from the best estimated value. This finds solutions at a series of depths, providing an indication of the sensitivity of the depth estimate (for that accepted shape assumption). Variation in the other (also unknown) parameters can generally compensate quite effectively for the offset depth value, indicating the limited sensitivity to depth. Unfortunately, non-uniqueness precludes determination of a statistically valid probability to associate with an estimated depth. However, from a series of inversion solutions at different depths, an interpreter can at least make a justified decision as to the appropriate depth to terminate a hole, should be source not have been intersected.

**Remanent magnetisation as a cause for incorrect location of drillholes**

Most magnetic field interpretation is undertaken on the simple (and somewhat lazy) assumption that induced magnetisation is the only cause of measured anomalies, and that it is a sufficient basis for their interpretation. However, there are substantial departures from this assumption, namely due to the effects of remanent magnetisation, self-demagnetisation and anisotropy of magnetic susceptibility. 

*Figure 1* shows two synthetic total-field magnetic anomalies, due to a simple dipole source placed in the geomagnetic field at Darwin and on the border of the Northern Territory and South Australia. Both anomalies are predominantly positive, with a minor negative to the south. The more southerly anomaly in a steeper inclination field (closer to the pole) has a less pronounced negative. These expected anomaly shapes are modified by more complex source geometry, such as sheets or pipes, particularly if these are plunging. For a compact source, any substantial departure from this pattern suggests the presence of a magnetisation that is not in the local geomagnetic field direction. The most common reason for substantial departures of magnetisation direction is the presence of remanent magnetisation, but for strongly magnetised sources, a second cause may be self-demagnetisation effects. The highly magnetised ironstones at Tennant Creek (Farrar 1979, Hoschke 1991) are a famous example of rotation of magnetisation by self-demagnetisation, where the strong internal secondary field rotates the magnetisation towards the plane of the body, and this has been recognised as a problem in locating source bodies in that region. If the apparent susceptibility of a modeled source body exceeds about 0.2 SI, then it is advisable to use a specialised code that incorporates self-demagnetisation effects, and as susceptibilities approach 1 SI or more, this is essential (not all geophysical inversion and modeling codes include provision of self-demagnetisation capabilities).

As well as having a magnetic susceptibility, ferromagnetic minerals generally carry a remanent magnetisation. If a grain is large enough to be a multi-domain magnet, then this remanent magnetisation is quite easily reset by movement of the domain walls, which over time, can happen at low temperatures, so that remanent magnetisation can track the present field, and act to accentuate the induced magnetisation, which is in the same direction. However, for smaller, elongate or sheet-like grains, the magnetisation...
may be carried by single domain or pseudo-single domain grains, and magnetisation directions quite different to the present field can be retained over geological timespans. In measurements on rock samples, the ratio of remanent to induced magnetisation, known as the Koenisberger Ratio or ‘Q factor’, is as commonly found to be above 1 as below 1. If a remanent magnetisation is a significant proportion of the total magnetisation and is rotated from the present field direction, then interpretation of the resulting magnetic anomaly, on the assumption that it is due to an

![Figure 1. Dipole total magnetic intensity (TMI) anomalies for a geomagnetic field setting as at (a) Darwin, and (b) Northern Territory/South Australia border.](image1)

![Figure 2. Example anomalies due primarily to remanent magnetisation from Tennant Creek (contrast anomaly pattern with those in Figure 1).](image2)
induced magnetisation, will result in the source body being mis-positioned. Some interpreters use RTP transforms in the expectation that this will position anomalies directly over the source bodies, but the standard RTP transform incorporates an inherent assumption that magnetisation direction is parallel to the geomagnetic field direction (if the magnetisation direction is known or estimated, then a more advanced RTP transform can be used which will allow substitution of that direction). An alternative and superior transform is the total gradient transform, which has limited sensitivity to magnetisation direction.

Several proven methods to estimate magnetisation direction from analysis and interpretation of magnetic field data exist, but these are not yet routinely used in magnetic field interpretation, and it is this neglect of remanent magnetisation which is the most common cause of drilling failing to intersect targets defined from magnetic field interpretation. CSIRO, in conjunction with Geoscience Australia, are preparing a web-delivered database of magnetic anomalies across Australia recognised to be substantially due to remanent magnetisation, from which estimated magnetisation directions, and in some cases source models can be downloaded. Figure 2 shows two magnetic anomalies from the database. These anomalies are located west of Tennant Creek, and are due to magnetisations rotated by more than 90° from the local geomagnetic field direction. The presentation accompanying this abstract highlights the issues of determining magnetisation direction for more reliable definition of drill targets, using Northern Territory examples from the forthcoming anomaly database.

Conclusions

The following checklist is recommended to better justify targets for drilling, and hopefully reduce the number of boreholes that fail to intersect their targets:

• Base the selection of drilling targets on parametric inversion of magnetic field data, rather than on automated depth estimation methods or image analysis.
• Search out any measured physical property values and take advantage of any opportunity to measure physical properties, including remanent magnetisation, as an integral part of the exploration program.
• Perform a series of inversions with depth offsets to bracket the best estimated depth, as a sensitivity analysis of that depth value, and as a basis to make decisions if the drillhole does not intersect the body at the expected depth.
• Be alert to the expressions of remanent magnetisation in magnetic field imagery and use transforms such as total gradient, which minimise remanence effects, in preference to RTP, which can be substantially distorted by it.
• Include remanent magnetisation as a free parameter in suitably structured inversions, in the expectation that most magnetic anomalies will have some contribution from remanent magnetisation, rather than considering the presence of remanence to be a special case.
• Be alert to nearby recorded occurrences of remanent magnetisation (to be made more conveniently available at the end of the year in the national Australian remanent magnetisation database), as these are acquired through geological events that may be widespread, affecting many magnetic sources within a broad region, and in many cases, with common anomaly patterns.

References
